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Assessment of Accuracy and Repeatability of Verbal Exertion Estimation in the Presence of Fatigue

By Matthew Klosner

A Thesis Submitted
in Partial Fulfillment
of the Requirements
for the Degree of
Master of Science
in Industrial Engineering

Industrial and Systems Engineering Department
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By

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Abstract

Occupational ergonomics has long focused on physical exertion as a key to the prevention of musculoskeletal injuries. Traditionally, objective measurements of forceful exertion such as electromyography (EMG) and direct force measurement have been used to assess exposure to forceful exertion. However, these measurements are often not practical for occupational settings due to their cumbersome and costly nature. As a result, psychophysical magnitude estimation may be used, in which human subjects verbally estimate the magnitude of an exertion. Despite an abundance of research on verbal estimation, its repeatability and the effects of fatigue on estimation accuracy have not been sufficiently assessed. An understanding of these factors is critical for the successful implementation of verbal estimation in occupational settings. The objectives of this research were to quantify the short and long term repeatability of psychophysical magnitude estimation as well as analyze the effect of fatigue on the accuracy of estimation.

Fifteen subjects performed two experiments separated by one week, in which they performed verbal estimation of submaximal forces. In addition to testing for repeatability, subjects were systematically exposed to muscular fatigue to evaluate its effect on accuracy. The results show that verbal estimation is repeatable in both the short and long term for submaximal exertions. In addition, the presence of muscular fatigue was shown to have a detrimental effect on the accuracy of estimation. On average, the estimation accuracy decreased 7.56% MVC in the presence of fatigue.

Table of Contents

List of Tables

List of Figures

List of Formulas

Section 1

Introduction

Workplace ergonomics has long focused on physical exertion as a key to the prevention of musculoskeletal injuries. Overexertion of a muscle or group of muscles, either through a one time event or the build up of repetitive exertions leads to injuries. Thus, it is imperative to have a good understanding of the amount of physical exertion needed to perform a work task. This may seem like a very simple notion because it is conceptually straightforward to assess the physical demands of most work tasks. The challenge however arises from the lack of accurate tools to effectively assess the physical demands of the work task.

Traditionally, objective measurements of forceful exertion such as electromyography (EMG) and direct force measurement have been used whenever a truly objective measurement is needed. However, these objective strength measurements are often not practical for occupational settings due to their cumbersome and costly nature. As a result, worker estimates of their physical exertion intensity are often used. However, these subjective measurements carry with them a question of accuracy.

A substantial amount of research has been performed on psychophysical magnitude estimation. These studies have sought to evaluate the circumstances which could influence an individual's ability to estimate physical exertion, such as training and exertion type (tool variation). However, limited research has examined how fatigue affects psychophysical magnitude estimation.

Fatigue as a physical and mental result of physical exertion has been explored considerably. Research has examined everything from the biophysical causes of fatigue to the endurance limits of different muscle groups in performing tasks. The research, however, is very sparse when evaluating how aware people are of their fatigue level and their strength when fatigued. This awareness of fatigued strength is important since a worker at the end of a 12-hour shift could be put at risk by trying to lift something heavy that they were able to safely lift at the beginning of their shift, all due to a lack of awareness of their current (fatigued) strength.

Workplace ergonomics is currently without a practical and proven method to evaluate the amount of exertion required to perform work tasks. As a result, researchers and practitioners are left with costly and cumbersome equipment or a subjective verbal estimate from the worker performing the task. Since questions remain over the validity of worker estimates, this study aims to evaluate the accuracy of psychophysical magnitude estimation while examining the effect of fatigue on these estimations to determine if worker estimation is an acceptable method of evaluating task acceptability.

1.1 Problem Statement

The objective of this thesis is to determine the accuracy and repeatability with which subjects can estimate the magnitude of submaximal exertions and what role fatigue plays in the accuracy of these estimated physical exertions during hand grip tasks. Additionally, this study will evaluate the accuracy with which subjects can quantify their fatigue level as a proportion of their (non-fatigued) maximum strength (MVC).

Section 2

Literature Review

2.1 Repetitive Motion Injuries of the Upper Extremities

A pressing concern in workplace ergonomics is repetitive motion injury. Repetitive motion injuries are injuries to the musculoskeletal and nervous systems caused by the combined effects of repeated motions, forceful exertions, awkward or sustained postures, or vibration. Also known as cumulative trauma disorders, repetitive strain disorders, and repetitive stress syndrome, RMI's develop gradually over time and can affect nerves, tendons, and muscles all over the body, and are especially prevalent in the upper extremities (fingers, hands, wrists, arms, shoulders, upper back, and neck). In a study of Washington State's workers compensation claims from 1987 through 1995, Silverstein, Welp, Nelson, and Kalat (1998) found that hand and wrist injuries were by far the most prevalent, with almost 1 in 100 employees suffering from a hand wrist disorder. RMI's of the hand and wrist (such as carpal tunnel syndrome or tendonitis) have limited workers performing all types of work tasks. Affected occupational tasks range from as simple as typing on a computer to operating a heavy vibrating tool (Palmer, Harris, & Coggon, 2007). Tasks that involve repetitive motions can put workers at risk for developing RMI's.

When repetitive tasks are combined with other risk factors, like forceful exertions, the risks of RMI's are amplified. Common assembly tasks, such as using a screwdriver or a pair of pliers, are often identified as areas of concern due to their repetitiveness and the high forces required (Kilbom, 1994; Latko, Armstrong, Franzblau, Ulin, Werner, Albers, 1999; Palmer et. al, 2007; Silverstein, Fine, & Armstrong, 1986; Viikari-Juntura & Silverstein, 1999). Additionally, high repetition has been found to be a greater risk factor for RMI's than high forces (Silverstein, Fine, & Armstrong, 1987), which seems to point out common assembly tasks as high risk for an RMI.

In order to identify tasks as high risk for RMI's, it is important to have a thorough understanding of the task and its requirements. In determining the force requirements for a task, there are several techniques available.

2.2 Force Measurement Techniques

Several force measurement techniques are available to evaluate the exertion needed to perform a task. In choosing between these techniques, there appears to be a tradeoff between cost, ease of use, and accuracy.

2.2.1 Direct Force Measurement

Direct force measurement is a credible method to gather data on the force requirements of a job. Direct force measurement uses some type of a force gauge or sensor to measure the actual force needed in performing a task. Quite obviously, this is going to produce the most accurate measurements as to the force required. As a result of the accepted accuracy of direct force measurement, it is often used as the "gold standard" for laboratory testing. Several studies have used direct force measurement as their only force measurement for measuring hand grip force; when quantifying the reliability of an endurance test (Capodaglio, Maestri, & Bazzini, 1997) or when establishing normative data for adult capabilities (Mathiowetz, Kashman, Volland, Weber, Dowe, & Rogers, 1984). Other studies have used direct force measurement in conjunction with other exertion measurement techniques when evaluating handgrip force, such as electromyography (Duque, Masset, & Malchaire, 1995; Iridiastadi & Nussbaum, 2006), psychophysical magnitude estimation (De Serres & Fang, 2004; Spielholz, 2006), or both (Grant, Habes, & Putz-Anderson, 1994; Koppelaar & Wells, 2005; Marshall, Armstrong, & Ebersole, 2004).

However, practical considerations often lead practitioners of industrial ergonomics away from direct force measurements. Although ideal for laboratory activities, the gauges needed to assess force are quite expensive, require specialized knowledge to use, and may not be adaptable to the specific task. If the task is adaptable, it can be very time consuming to fit a force gauge to the task, requiring customized handles on the tool(s) being used. If this is not enough, most sensors have to be attached to the hands and fingers, causing workers to deviate from normal practices (Jensen, Radwin, & Webster, 2001). Additionally, the precision produced by the force gauges is often in excess of what is required in a workplace setting (Koppelaar & Wells, 2005). As a result of the impracticality of direct force measurement, indirect force measurement methods are being integrated into the evaluation of forceful exertions.

2.2.2 Electromyography (EMG)

EMG is a technique of tracking the electrical potential of muscles as they are at rest and as they contract (Rau, Schulte, & Disselhorst-Klug, 2004). Surface electromyography may be used as an indirect method of gathering data on forceful exertions. By monitoring the muscle contractions, it is possible to predict the forces being applied through mathematical modeling (Duque et. al, 1995). As a result, EMG has been used in numerous handgrip force measuring experiments, mainly in conjunction with other measures of applied force, such as direct force measurement (Duque, et. al 1995; Iridiastadi & Nussbaum, 2006) and psychophysical scales (Grant et. al, 2004; Koppelaar & Wells, 2005; Marshall et. al, 2004). However, the use of EMG to provide objective data on exertion intensity relies on several factors, such as the distance between the muscle and the recording electrodes, which are practitioner dependent (Rau et. al, 2004). Similarly, surface electrodes are susceptible to changes in posture since the skin they are located on can shift above the underlying muscle they are supposedly monitoring (Duque et. al, 1995). Thus, the same experiment can lead to different conclusions based only on the location of the EMG sensors (Mercer, Bezodis, DeLion, Zachry, & Rubley, 2006). Although surface electromyography allows researchers to map muscle activity to force produced, the process is still complicated and can lead to practitioners examining simpler methods.

2.2.3 Psychophysical Magnitude Estimation

Psychophysical magnitude estimation is another indirect method of forceful exertion evaluation used both in laboratory settings and in the field. This is mainly due to the ease and simplicity with which it can be performed. With psychophysical magnitude estimation, the subject is asked to evaluate, often as a percentage of their maximum strength, the amount of force needed to perform a given task or job. The obvious drawback to this indirect method is the subjectivity associated with having the subject estimate based on their personal strength, leading to a loss of accuracy in the estimation.

One of the key drawbacks to more objective methods of measuring physical exertion, and in turn benefits of psychophysical magnitude estimation, is the costly and cumbersome nature of the necessary equipment. Psychophysical methods are much simpler, requiring less investment (both time and money) in order to obtain results (Sinclair, 1995). No elaborate (expensive) equipment is needed. The subject only needs to perform their task as they normally would, with the possibility of some training beforehand, and provide an estimate of the magnitude of an exertion in terms of their maximum capability.

Subjectivity is a major weakness of psychophysical magnitude evaluation since a common perception is that it may lead to a loss of accuracy in the force estimate. This however may not be as large a problem as first thought, especially for complex tasks, where psychophysical estimates have been shown to be more accurate than EMG (Grant, Habes, & Putz-Anderson, 1994). Laboratory settings generally attempt to isolate factors such as fatigue, experience, or exertion type to determine what effect they alone have. This approach often overlooks the interactions between these effects, which can be even more significant than the effects of the individual conditions. One of the key benefits of psychophysical magnitude estimation is that it incorporates a great deal of information from various sources within the body (muscles, joints, and nerves) and integrates them together (Borg, 1990). Even though the information is coming from multiple sources, the accuracy of the estimate has been found not to depend on the specific muscle group used to create the exertion (Chin, Bishu, & Hallbeck, 1995). Likewise, Marshall et. al (2004) found that the error in estimation did not significantly differ over different tasks as long as the tasks utilized the same general muscle groups.

In evaluating the accuracy of exertion estimation, varying results have been obtained, although all conclude that psychophysical evaluation of exertion intensity is a valid method to collect data of exertion force in general industrial settings. A majority of the previous research has found that subjects tend to overestimate forces at low levels (Boa & Silverstein, 2005; De Serres & Fang, 2004; Spielholz, 2006). Other research has found that subjects tend to overestimate across all force levels, although not significantly at high levels (Marshall et. al, 2004). Meanwhile, Wiktorin, Selin, Ekenvall, Kilbom, & Alfredsson (1996) found that subjects overestimated the force needed to reproduce low force levels and underestimated the force required to match high force levels. Additionally, some research has pointed in the opposite direction. Chin (1995) found that subjects tended to underestimate the magnitude of the force across all force levels. Fairfax, Balnave, & Adams (1995) found no pattern in the error of the estimates, but that the variability was much greater for midrange submaximal exertions than for other exertions. Even with the slight error in estimation, the literature suggests that psychophysical magnitude estimation can be used in laboratory settings as well as the field since it provides reasonably valid data for a fraction of the cost and effort of other force measurement techniques.

Some research has studied the effects of training on the precision and accuracy of verbal magnitude estimation. Deeb (1999) found a significant improvement in the accuracy of the estimation if the subject was to estimate a weight in one hand while holding a known weight in the other hand. Spielholz (2006) also found an increase in accuracy due to training. However, the training in this study consisted of a maximal and several submaximal (as a percentage of MVC) exertions. The maximal exertion can be thought of as feasible for a workplace setting, where workers would be able to experience their maximum strength before evaluating other forces, but the submaximal training does not seem to be as practical in a workplace setting. It is hard to imagine how a worker could be guided to specific values other than their maximum without specific (expensive) equipment. Marshall et. al (2004) found that one maximal exertion produced before estimating force significantly improved the accuracy of the estimation. Training is one factor that has been found to significantly affect the accuracy of a subject to estimate their exertion, while other factors, such as muscular fatigue, have yet to be fully examined.

2.3 Muscular Fatigue and Endurance

Muscular fatigue can be defined as "a loss of maximal force-generating capacity that develops during muscular activity" (Lewis & Haller, 1991, p. S98) Reduced blood flow to the muscles and lactic acid buildup are the most widely accepted physiological causes for fatigue, although some research has disputed this for low level isometric contractions (Sjogaard, Savard, & Juel, 1988). Because fatigue is so common, it needs to be considered as a factor affecting the accuracy with which a subject can estimate their exertion since the subject may be fatigued when they are producing their exertion estimate. Previous research on verbal estimation (Marshal et. al, etc.) has used time delay or randomization to control or minimize the presence of fatigue.

2.3.1 Fatigue as a factor in Psychophysical Magnitude Estimation

A reduction in the ability of a muscle (or muscle group) to produce force should conceivably affect an estimate of an exertion. Under ideal settings, a decrease in muscular strength should lead to a corresponding increase in the exertion intensity needed to produce the same force. For example, consider if after a 30 minute hand grip task, a subject was able to produce 80% of their un-fatigued maximum strength. Then, suppose the subject was asked to estimate the force needed to perform a different task which required 60% of their un-fatigued maximum strength. When estimating the exertion required for this different task based on their current strength, the subject would theoretically estimate 75% since their current strength is less than their un-fatigued strength. This would assume that the subject was aware of the amount of their fatigue and that they were accurate in their exertion estimation. However, muscular fatigue can be intertwined with mental fatigue, amplifying the effects of the muscular fatigue, as shown by Chalder, Berelowitz, Pawlikowska, Watts, Wessley, Wright, and Wallace (1993) during subject scoring on a fatigue scale.

No research has been performed on the specifics of how aware a subject is of their level of fatigue (other than a binary assessment of "fatigued" or "not"). If a subject was not aware of their fatigue, then their psychophysical estimate of forceful exertion would become less accurate as the subject becomes more fatigued. At the same time, if it can be quantitatively proven that subjects are indeed aware of their fatigue level, then it is possible to go forward and evaluate the accuracy of psychophysical magnitude estimation when the subject is fatigued by treating the subjects' fatigue as just another factor. This ambiguity in fatigue awareness could potentially distort exertion estimates and thus it needs to be examined further. Although no research has examined awareness of fatigue level, *this study hypothesizes that subjects are not accurate in their awareness of their level of fatigue*. This was supported in initial pilot studies.

Minimal research has been conducted to examine the specific effects that fatigue may have on a subject's ability to estimate their exertion level. Of the research that has been done, subjects significantly underestimated weights while fatigued (Deeb, 1999).

However, this research did not look at any different levels of fatigue, only before the muscles were fatigued and after fatigue, where "fatigue" was defined as when a subject could no longer hold a predefined force. This study could have been improved by evaluating different levels of fatigue and observing the weight estimates at these different fatigue levels.

Other research has noted the effects of varying levels of fatigue on perceived exertion through long term tasks. Bystrom and Fransson-Hall(1994) noted an almost linear increase in perceived exertion over time with a constant force in intermittent hand grip tasks. This study did not evaluate the accuracy of the psychophysical ratings, however, only noting that they increased over time. But the increase in perceived exertion over time suggests that subjects were aware of their fatigue. This phenomenon of subjects' awareness of their fatigue has been observed in previous research through increases in exertion intensity over time with constant force in psychophysical estimation (Sjogaard, 1986; Bystrom & Fransson-Hall, 1994; Bystrom & Kilbom, 1990), but has not been thoroughly examined.

It is important to understand in practical terms just how fatigue can influence a subject's psychophysical magnitude estimation. For example, in an industrial application, suppose an employee is on hour nine of a ten hour shift. At this point, the subject may be fatigued and a practitioner must know whether their estimate of the magnitude of a particular exertion is accurate and reliable. Previous studies have attempted to eliminate fatigue as a variable by having recovery time between estimates and tasks (Marshall et. al, 2004), which leaves the question of a fatigued subject's ability to estimate their exertion unanswered. Directly associated with this is the subject's understanding of their fatigue level. If subjects are aware of their fatigue level, as shown by Bystrom & Fransson-Hall (1994), then they should be able to estimate their exertion as either a percentage of the total strength or as a percentage of their strength at whatever time they are performing the estimate (fatigued strength) with similar degrees of accuracy. If they are not aware of their fatigue level, their psychophysical magnitude estimation may not be appropriate for situations where subjects are fatigued before providing an exertion estimate. Based on the research cited above, *it is hypothesized that this experiment will show that the accuracy of psychophysical magnitude estimation decreases when the estimations are made from a fatigued state*.

2.3.2 Inducing Muscle Group Specific Fatigue

In order to study the effects of fatigue on a muscle group, it is important to first know the strength and endurance limits of the muscle group. Muscular endurance, also known as stamina, is the ability of a muscle to continue producing force over time despite fatigue. The length of the endurance time is dependent on the intensity of the effort (West, Hicks, Clements, & Dowling, 1995; Iridiastadi & Nussbaum, 2006), while sustained static tasks tend to induce fatigue much quicker than intermittent isometric static tasks (El ahrache, Imbeau, & Farbos, 2006). Bjorksten and Jonsson (1977) found that for intermittent static contraction, a mean force of contraction of 14.0% MVC was the endurance limit for arm strength over a 60 minute period. Additionally, the mean force for a continuous static contraction was found to be 7.9% MVC, again for arm strength over a 60 minute period.

Several studies have aimed to establish clear cut limits for muscular endurance as a percentage of MVC. However, the acceptable limits established in these studies have ranged from a mean contraction intensity of 17% MVC (Bystrom & Fransson-Hall, 1994) to 7.7% (Eksioglu, 2006) for intermittent handgrip tasks. This variability is in part due to the duration of the intended task, as the Bystrom and Fransson-Hall study examined 60 minute endurance while the Eksioglu study looked at endurance for an 8 hour shift. However, a majority of the research for intermittent handgrip tasks like the ones performed in this study found contraction intensities similar to those of Bystrom and Fransson-Hall(1994). Hagberg (1981) found that in both sustained isometric and intermittent isometric exercise, exertions above 15-20% MVC resulted in a rapid decrease in endurance time, although endurance time was elongated in intermittent isometric exercises. This was further backed up by research performed by Bystrom and Kilbom (1990), which found that local fatigue was not present during intermittent isometric handgrip tasks at 10% MVC. This study also found that in certain contraction-relaxation cycles, fatigue was not present for 25% MVC.

2.4 Repeatability of psychophysical magnitude estimation

Another key to the practical implementation of psychophysical magnitude estimation in the workplace is establishing its repeatability. An assessment method which gives highly accurate results one time and faulty results the next is of limited value since it's so unreliable.

Minimal research has been performed to determine the repeatability of psychophysical magnitude estimation. However, what has been performed has suggested that subject estimation of hand grip forces was reliable due to between-participant reliability coefficients which were moderate to good (Koppelaar & Wells, 2005).

Additionally, Kumar, Simmonds, and Lechelt (1994) found no significant difference in estimation accuracy between three trials of constant hand grip force estimation within young female subjects. The rather sparse research into the repeatability of psychophysical magnitude estimation makes it a prime area to be investigated further.

Some limited research has been performed on the ability of subjects to reproduce static forces without any feedback. Carlsoo (1986) found that subjects had a degree of precision of approximately 10% when repeating static forces several times in a row over a short duration, meaning that they were within 10% of the targeted force. Additionally, Wiktorin et. al (1996) found a high reproducibility when subjects performed familiar submaximal forces (tasks with which the subjects were familiar, like a baker simulating lifting a bag of flour). However, this study did not examine the reproducibility of unfamiliar forces, instead focusing only on forces with which the subjects would be familiar from their daily tasks.

Force matching for hand grip forces is another method of observing repeatability. When matching at a known force, force matching has been found to be quite accurate, especially when hand posture and upper arm positions are consistent (Bao & Silverstein, 2005). However, this research by Bao and Silverstein found that the instructions given to the subjects were of paramount importance, citing a reduction in variation due to improved instructions which narrowed the scope of the task (instructing subjects to reproduce the minimum force necessary as opposed to instructing them to reproduce the necessary force). Koppelaar and Wells (2005) found force matching to be moderately reliable over five different tasks which all simulated work activities, with coefficients of variation not dissimilar to direct measurement and EMG.

Based on the previous research by Kumar et. al (1994) and Wiktorin et. al (1996), *it is hypothesized that this study will find that psychophysical magnitude estimation does indeed have a high degree of repeatability*. This is further supported by the relative success of force matching and force reproducibility shown by Bao and Silverstein (2005) and Wiktorin et. al (1996), respectively.

Section 3

Methodology

3.1 Experimental Objective

The objective of this study was to evaluate the effects of force and fatigue on the accuracy of estimations of exertion intensity as well as evaluate the repeatability of psychophysical magnitude estimation. Additionally, this study aimed to quantify the accuracy with which subjects can identify the extent to which they experience fatigue.

3.2 Experiment Design

In this study, a repeated measures experiment was performed. An overview of the experiment is presented graphically in Figure 3.1. Two experiments, A and B, were performed with approximately one week in between the two experiments. Subjects were counterbalanced (approximately half performed experiment A first, while approximately half performed experiment B first) to eliminate any effects of the order of performance on the results.

In both experiments, subjects performed two replications of verbal submaximal exertion estimations. During each of the exertion estimation trials, subjects performed three estimates at each of a low, medium, and high force level. The order of force level presentation was randomized.

A delay occurred in between the replications of force estimation trials. During this delay subjects either performed a number of exertions designed to induce fatigue (experiment A) or subjects sat idle (experiment B).

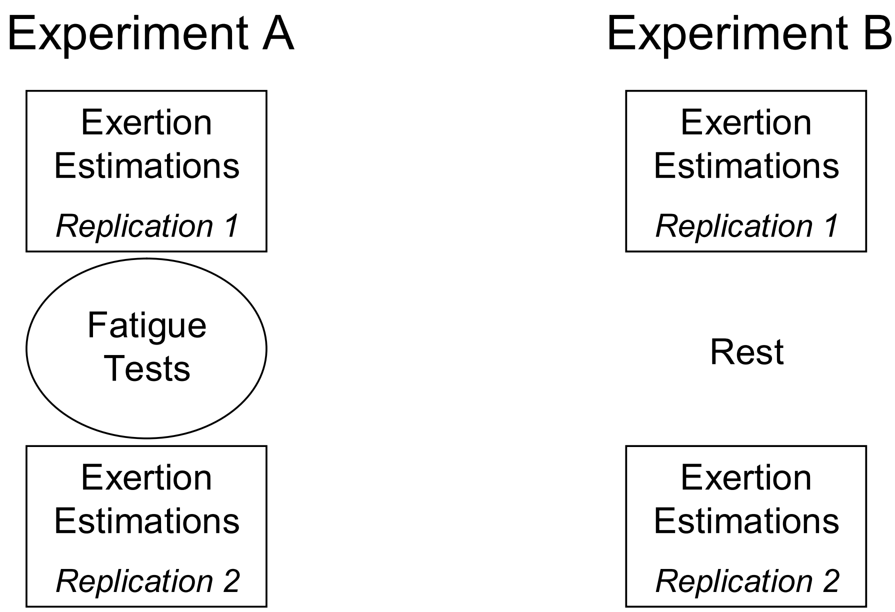


Figure 3.1 Overview of the experiment

3.3 Independent Variables

3.3.1 Experiment

The first independent variable was the experiment, which consisted of two levels (A, B). Over the course of this study, subjects participated in two separate experiments separated by approximately one week. The two experiments were counterbalanced to avoid the effects of learning. The two experiments, A and B, consisted of submaximal exertion estimations separated by a 30-minute delay between replications. During this delay, subjects either performed a number of exertions designed to induce fatigue (experiment A) or subjects sat idle (experiment B) (Figure 3.1).

3.3.2 Replication

The second independent variable was replication. For both experiments A and B, subjects performed two replications of submaximal exertion estimates. These replications were separated by 30 minutes consisting of either a number of exertions designed to induce fatigue (experiment A) or idle time (experiment B).

3.3.3 Force Level

The third independent variable was the force level which the subjects were asked to estimate. During each of the submaximal exertion estimation phases, subjects were asked to estimate forces as a percentage of their maximum strength (%MVC). These forces were in percentage of the subject's maximum strength and broken into three levels: low, medium, and high. The low forces were 10, 15, or 20% MVC while the medium forces were 40, 50, or 60% MVC and the high forces were 75, 85, or 90% MVC. Each force level was estimated three times; once for each value in the level in random order.

3.3.4 Fatiguing Task Force

The fourth independent variable was the force of the fatiguing task. There were three levels of forces used for the fatiguing task: 25% of the subjects MVC, 50% of the subjects MVC, or 75% of the subjects MVC. These levels were selected to induce increasing levels of fatigue, which is described later in further detail. Each subject performed one task at each of the three force levels. The order of the forces was selected randomly for each subject.

3.4 Dependent Variables

3.4.1 Error in Submaximal Exertion Estimation

In experiments A and B, the difference between the verbally estimated force required to perform the task and the actual force required was a dependent variable. This is defined in Formula 3.1 and is consistent with other research (Marshall et al, 2004). The actual force the machine is set to, as a percentage of the subjects MVC, was known only by the investigator and was recorded with the subject's estimate of the force required to perform the task. The difference between these two values represents the error in force estimation.

$$\begin{matrix} \textit{Estimated} \\ \textit{Force} \end{matrix} - \begin{matrix} \textit{Actual} \\ \textit{Force} \end{matrix} = \begin{matrix} \textit{Exertion} \\ \textit{Estimation Error} \end{matrix} \qquad 3.1$$

3.4.2 Error in Fatigue Estimation

Within experiment A, the difference between the perceived strength loss due to fatigue and the actual strength loss was another dependent variable. This is defined in Formula 3.2. A maximum strength (MVC) measurement was performed immediately prior to and following the fatiguing task, with the difference being the actual strength loss. Immediately following the fatiguing task, the subject was asked to estimate their current strength as a percentage of their fully-rested strength, providing the perceived strength loss. The difference between these two values is the error in fatigue estimation.

$$\begin{matrix} \textit{Estimated} \\ \textit{Strength} \\ \textit{Loss} \end{matrix} - \begin{matrix} \textit{Actual} \\ \textit{Strength} \\ \textit{Loss} \end{matrix} = \begin{matrix} \textit{Fatigue} \\ \textit{Estimation Error} \end{matrix} \qquad 3.2$$

3.4.3 Subjective Rating of Perceived Discomfort

Also within experiment A, subjective rating of perceived discomfort served as a dependent variable. Subjects were asked to verbally report their perceived discomfort in their hand and wrist on the CR-10 scale (Borg, 1990). Prior to starting the experiment, subjects were shown the rating scale and instructed how to use it. Perceived discomfort was included as a dependent variable in order to ascertain the relationship between perceived discomfort and fatigued strength estimation error.

3.5 Subjects

A total of 15 subjects (9 male, 6 female) participated in this study. All subjects were full-time college students at either the undergraduate or graduate level. No subjects reported having any hand or wrist injuries to their dominant hand in the year prior to their participation. Two subjects classified themselves as ambidextrous. These subjects performed the tasks using the hand which felt the most natural in performing the task. Subjects had a mean age of 22.3 years (21-25) and a standard deviation of 1.03 years. Subjects had a mean height of 68.53 inches (61-74) with a standard deviation of 3.29 inches.

3.6 Experimental Procedure

Subjects were first informed of the purpose, risks, and procedure used in the study. Subjects were then required to read and sign an informed consent form approved by the RIT Institutional Review Board Committee (Appendix A). Once the subject had signed the informed consent form, demographic information, such as the subject's dominant hand and height, was collected. Subjects were then introduced to the work simulator machine, which along with the Simulator II software has been found previously to be a reliable method for determining and quantifying grip forces (Beaton, O'Driscoll, & Richards, 1995; Powell, Zimmer, Antoine, Baruch, Bellian, Morgan, & Edlich, 1991).

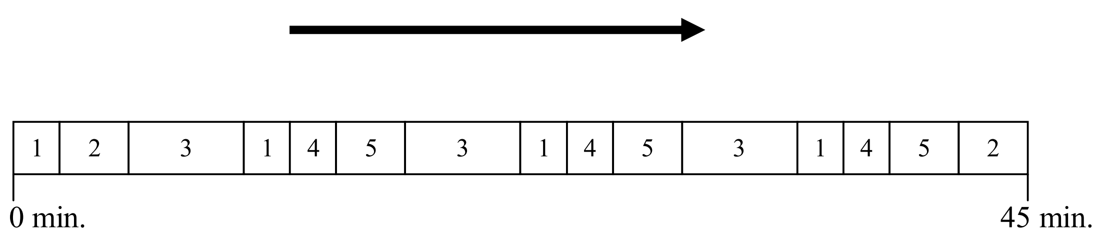
The machine was then adjusted to the subject's height so that their wrist was at a neutral posture with minimal radal/ulnar deviation or flexion/extension (see Figure 3.2). At this point, subjects were also instructed on how to grip the apparatus, having the hand positioned so that it comfortably grasped the upper portion of the apparatus. The forefinger was at the tip of the lower handle and the inside of the base of the thumb pressed against the protruding metal perpendicular to the axis of the handle with the heel of the palm resting on the upper handle (see Figure 3.2).

Figure 3.2 – Hand position on apparatus

Subjects were also informed to use only their hand grip strength when squeezing the handle, not their body weight or the contribution created by using other segments in their upper body. This was monitored by watching the subject closely throughout the experiment to ensure subjects were consistently using only their hand grip strength.

3.6.1 Experiment A – Fatigue Trials Between Submaximal Estimation Trials

Experiment A began with the subjects performing a MVC test (described in section 3.6.1.1) to establish their maximum grip strength. Following the acquisition of their maximum grip strength, subjects estimated their exertion as they squeezed the apparatus at nine different submaximal forces. A fatiguing task (described in section 3.6.1.3) followed the exertion estimates, and was designed to fatigue the muscles of the hand and forearm. After the fatiguing task, another MVC test was performed to determine the subject's actual strength at that point, which they were then asked to estimate as a percentage of their original strength before the fatiguing task. This cycle (MVC test, fatiguing exertion, MVC test and estimates) was repeated two more times using different fatiguing force levels. After the third fatiguing exertion, subjects performed the second replication of submaximal exertion estimates. A timeline of the procedure can be seen in Figure 3.3.



1: MVC Measurement
2: Submaximal Exertion Estimations
3: Five Minute Recovery Period
4: Fatiguing Exertion
5: MVC Measurement / Fatigue Strength Estimate / Rating of Perceived Discomfort

Figure 3.3 - Timeline for experiment A

3.6.1.1 MVC Measurement

Experiment A included a total of seven measurement phases of the subject's maximum grip strength (MVC tests); as the first measurement in the experiment and then preceding and following each of the three fatiguing tasks. Three maximum exertion measurements were taken for each phase and the average was used as the subject's maximum at each test, since previous research has found grip strength to be more consistent in measurement sets of three consecutive measurements than in single measurements (Ertem, Harma, Cetin, Elmali, Yologlu, Bostan, and Sakarya, 2005; Mathiowitz, Kashman, Volland, Weber, Dowe, and Rogers, 1985). Participants were allowed 20 seconds rest between exertions during each phase as a method of preventing their fatigue level from changing during the phase. For each of the trials, subjects were informed to slowly ramp up to their maximum force over a 2-4 second period and then hold their maximum for a 1-3 second steady state period (Chaffin, 1975).

3.6.1.2 Submaximal Exertion Estimation

The submaximal exertions were randomly selected. Each test consisted of three estimations from each of three exertion levels: low (10, 15, and 25%MVC), medium (40, 50, and 60%MVC), and high (75, 85, and 90%MVC) in random order. The exertion estimation test occurred immediately after the first MVC test and again after the final MVC test for both experiments. The resistance on the work simulator was set to the specified force and the participant was told to "Please estimate, as a percentage of your most recently measured maximum, the exertion intensity needed to budge the handle." The participant was at no time aware of the actual force, but was thought to have at least some recollection of their maximum, since they had already performed their MVC test. This protocol is consistent with that of Marshall et al. (2004) in which a maximum exertion benchmark was provided as an initial benchmark. A twenty second break occurred between estimates as an attempt to prevent the subject from recovering from the level of fatigue reached after the submaximal fatiguing exercises.

3.6.1.3 Fatiguing Exertions

Each participant performed three fatiguing tasks between estimation periods during experiment A. These fatiguing tasks consisted of a 60 second sustained static exertion at a low force (25% MVC), medium force (50% MVC), or high force (75% MVC) submaximal target exertion level. Before beginning the task, the subject was instructed to hold their force as best they could for 60 seconds to the center dashed target line shown on the screen (Figure 3.4).

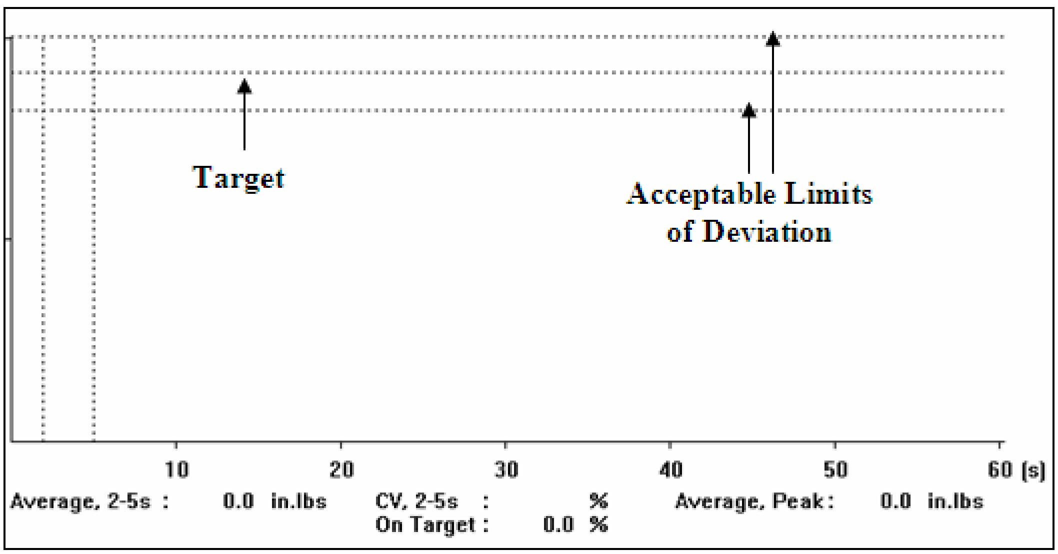


Figure 3.4 - Fatiguing task display

The upper and lower dash lines serve as boundaries 10% above and below the target, so for the low force fatiguing task (sustained force of 25% MVC), they represent 27.5 and 22.5% of the subject's MVC, while for the medium force fatiguing task (sustained force of 50% MVC) they represent 55 and 45% of the subject's MVC and for the high force fatiguing task (sustained force of 75% MVC) they represent 77 and 63% of the subject's MVC. If the subject's force dropped below the bottom dashed line (-10%) for more than 3 continuous seconds, they were deemed fatigued and the fatiguing task was stopped short of the sixty second duration. The subjects were able to follow their progress and adjust the applied force as needed via the line on the display (Figure 3.5). The exertion required in all three fatiguing tasks is significantly above the guidelines set to avoid fatigue for sustained static contractions by Bjorksten and Jonsson (1977), even though their period of time was one hour compared to this experiment's sixty seconds.

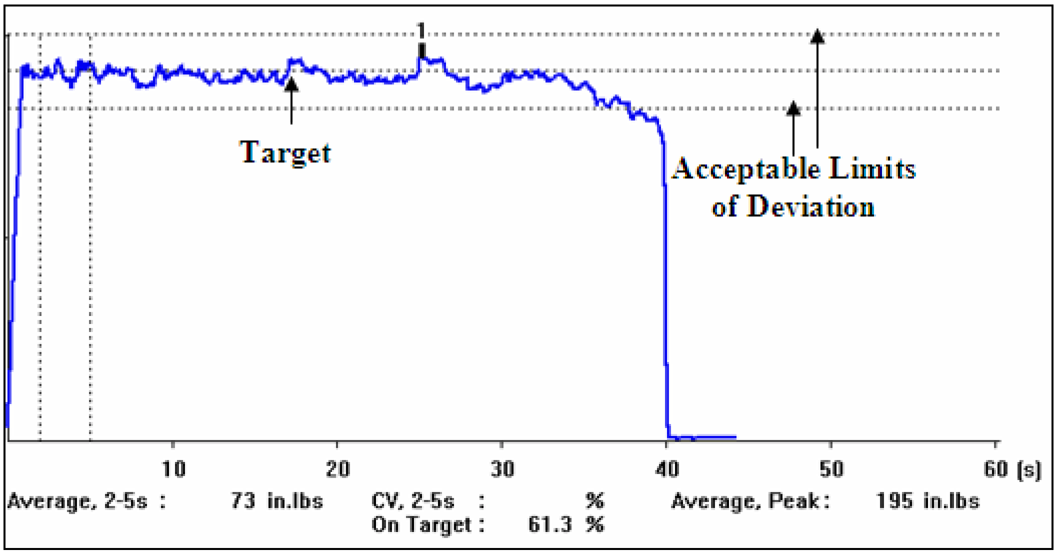


Figure 3.5 - Fatiguing task display while subject performs fatiguing task

Additionally, the high force fatiguing task falls above the endurance line for one minute tasks on the Rohmert curve (Rohmert, 1960) (Figure 3.6), suggesting that if maintained for one minute, it should significantly fatigue the hand and forearm muscles. Based on the Rohmert curve, the high force task at 75% MVC should only be performable for approximately 45 seconds, while the medium force task at 50% MVC should be performable for approximately 1.25 minutes and low force task at 25% MVC should be performable for approximately 3.5 minutes. Since the medium and low force tasks fall below the maximum endurance line for one minute static contractions, it suggests they should induce less fatigue and be sustainable by the subjects (Rohmert, 1960). Following the conclusion of each fatiguing task, subjects used the Borg CR-10 (Borg, 1990) scale to estimate their discomfort while performing the fatiguing task.

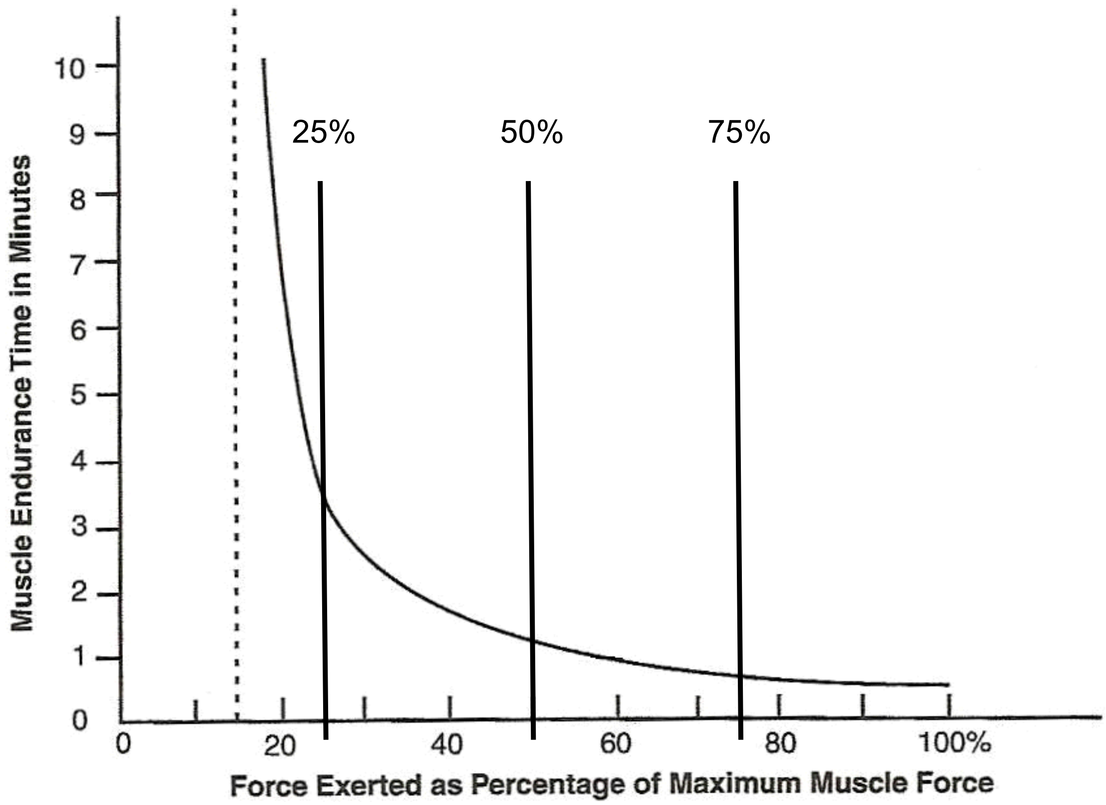


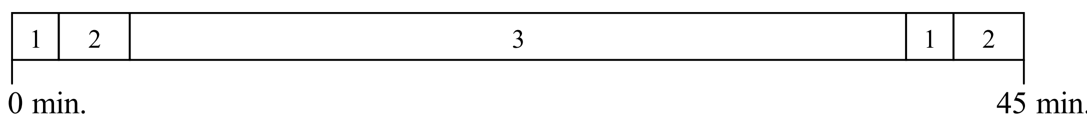
Figure 3.6 Rohmert curve (Rohmert, 1960).

3.6.1.4 Fatigued Strength Estimation

At the end of each fatiguing exercise, an estimate of the subject's fatigue was acquired. Immediately after finishing the MVC test, subjects were asked "Please estimate, as a percentage of your initial maximum prior to the fatigue task, your current maximum ability." Again, the participant was not aware of the actual strength measurement and could not, therefore, calculate what the strength decrement was.

3.6.2 Experiment B

Experiment B began the same as experiment A, with the subjects performing a MVC test to establish their maximum grip strength. Following the acquisition of their maximum grip strength, subjects estimated their exertion as they squeezed the apparatus at nine different forces as described previously for experiment A. Once the exertion estimates were completed, the subjects were asked to sit and relax for a 30 minute period. This rest period was for the same duration as the fatiguing task and strength measurement portion of experiment A. Following the 30 minute rest period, the subject's were again asked to estimate their exertion intensity 9 times for different submaximal exertions. A timeline for experiment B can be seen in Figure 3.7.



1: MVC Measurement
2: Submaximal Exertion Estimations
3: Rest Period

Figure 3.7 - Timeline for experiment B

3.6.2.1 MVC Measurement

The MVC measurements in experiment B were performed as they were in experiment A. However, experiment B contained just two MVC measurements: one to begin the experiment and one following the rest period. Please see section 3.6.1.1 for details about how the MVC measurements were conducted.

3.6.2.2 Submaximal Exertion Estimations

The exertion estimations in experiment B were performed as they were in experiment A, with the exception that the second replication was not performed under fatigue. Please see section 3.6.1.2 for details.

3.7 Data Analysis

A repeated measure analysis of variance was performed on the dependent variable error in force estimation (formula 3.1) using the independent variables experiment (A, B), replication (1^{st}, 2^{nd}), and force level (low, medium, high). Post-hoc comparison of the means was performed using the Tukey method.

From the fatigue tasks performed within experiment A, a single factor repeated measure analysis of variance was performed on both dependent variables error in fatigue estimation (formula 3.2) and perceived discomfort using the independent variable fatiguing task force (low, medium, high). Post-hoc comparison of the means was again performed using the Tukey method. All data was analyzed using the Minitab statistical software package.

Section 4

Results

4.1 Accuracy of Exertion Estimation

Exertion estimation error was calculated by subtracting the actual force from the estimated force (formula 3.1) and the descriptive statistics are shown in Table 4.1. The negative mean indicates an underestimation of exertion by the subject.

Table 4.1 Means and standard deviations of submaximal exertion estimate error (estimated force – actual force). * denotes mean is statistically different from zero.

Experiment	Replication	Force Level	Mean	Standard Deviation
A	1	Low	-2.33	8.37
		Medium	-2.00	19.78
		High	-11.67*	16.51
	2	Low	-5.11*	8.22
		Medium	-15.33*	18.81
		High	-18.22*	15.27
B	1	Low	-2.00	9.13
		Medium	1.89	18.81
		High	-5.56*	12.53
	2	Low	-4.33*	9.51
		Medium	-3.11	19.31
		High	0.33	9.44

Six conditions were significantly different than zero ($p < 0.05$). These conditions were: experiment A, replication 1, high force level; experiment A, replication 2, low force level, medium force level, and high force level; experiment B, replication 1, high force level; experiment B, replication 2, low force level.

A three-factor analysis of variance was then performed on the data to determine the statistical significance of the exertion force level (low, medium, or high), replication (1 or 2), and experiment (A or B) on the error level of the estimations (estimated %MVC

– actual % MVC). The analysis of variance is summarized in Table 4.2 and can be seen in its entirety in Appendix C.

Table 4.2 Three-factor analysis of variance of submaximal exertion estimation error.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Subject	14	36901.2	36901.2	2635.8	18.15	0.000
Replication	1	2180.0	2180.0	2180.0	15.01	0.000
Force Level	2	2820.1	2820.1	1410.0	9.71	0.000
Experiment	1	6580.0	6580.0	6580.0	45.30	0.000
Replication*Force Level	2	1900.1	1900.1	950.0	6.54	0.002
Replication*Experiment	1	1688.9	1688.9	1688.9	11.63	0.001
Force Level*Experiment	2	3199.0	3199.0	1599.5	11.01	0.000
Replication*Force Level*Experiment	2	836.8	836.8	418.4	2.88	0.057
Error	514	74661.0	74661.0	145.3		
Total	539	130767.2				

4.1.1 Effect of Replication

The replication * force level interaction effect ($F(2,514) = 6.54$, $p = 0.002$) and the replication * experiment interaction effect ($F(1,514) = 11.63$, $p = 0.001$) were significant along with the main effect of replication ($F(1,514) = 15.01$, $p < 0.001$). These interaction and main effects are summarized in Figures 4.1, 4.2, and 4.3. Though the main effect of replication was statistically significant (Figure 4.1), with the second replication significantly greater than the first ($p < 0.0001$), the replication * experiment interaction effect was also statistically significant and is of the most importance in evaluating the effect of replication.

As shown in Figure 4.2, the driving factor for the variable replication is the replication * experiment interaction. In experiment B (no fatigue), replication 1 was not significantly different than replication 2 ($p = 0.9936$), but in experiment A (with fatigue) replication 1 was significantly less than replication 2 ($p = 0.0002$). This difference was not only significant, but of such magnitude (7.56% MVC) that it appears to dominate the effects involving replication. The experiment was designed so that subjects would be fatigued during experiment A, and this was verified by the data. The mean strength loss (fatigue) of subjects prior to performing the replication 2 of experiment A was 13% MVC (standard deviation of 11% MVC), verifying that subjects were fatigued prior to the second replication of exertion estimates in experiment A.

The replication * force level interaction effect, shown in Figure 4.3, was also significant ($F(2,514) = 6.54$, $p = 0.002$). The only statistically significant difference between the replications happens at the medium force level ($p = 0.0008$), where the mean error for replication 1 is -0.04% MVC while the mean error for replication 2 is -9.10% MVC. This increase in error from replication 1 to replication 2 is also seen in both the low and medium force levels, although the difference is not significant. The general increase from replication 1 to replication 2 for all force levels is likely driven by the pronounced effect seen in experiment A (shown in Figure 4.2).

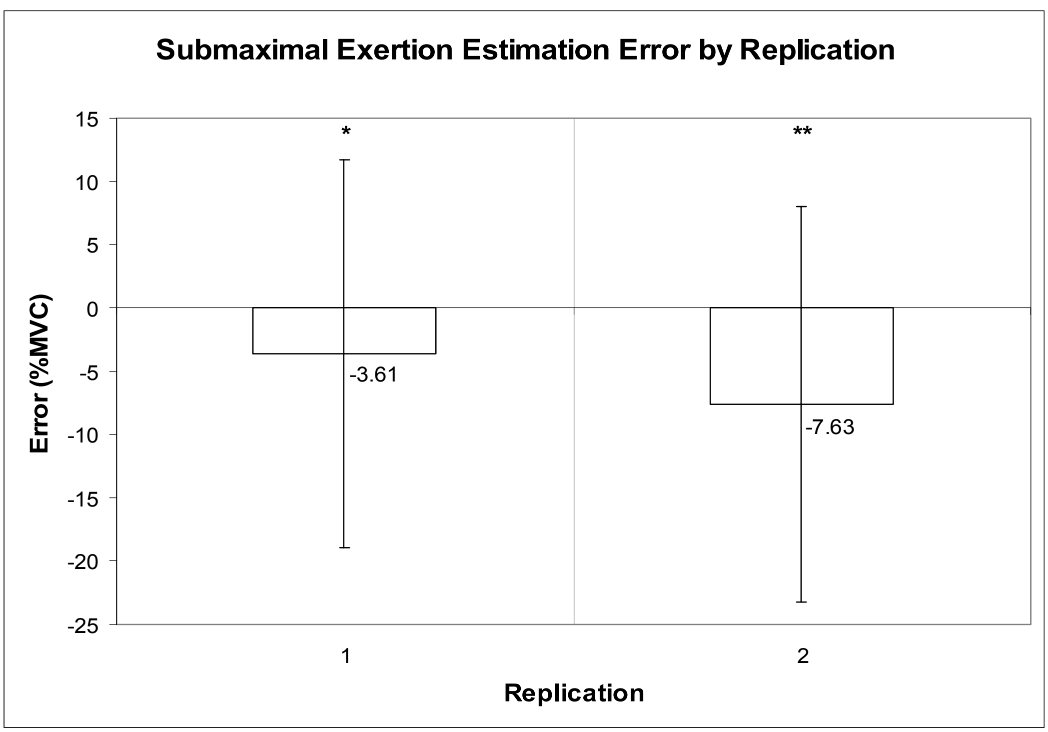


Figure 4.1 Main effect of replication on submaximal exertion estimation error. The number of *'s represent significant differences ($p < 0.05$) between conditions.

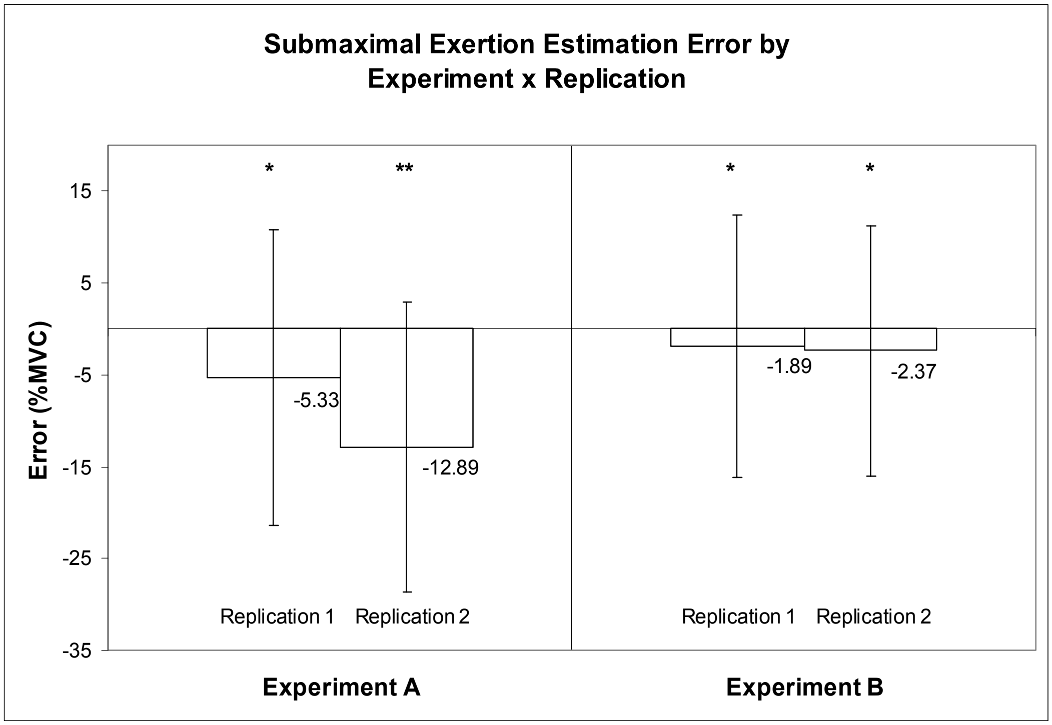


Figure 4.2 Interaction effect of replication and experiment on submaximal exertion estimation error. The number of *'s represent significant differences ($p < 0.05$) between conditions.

Figure 4.3 Interaction effect of replication and force level on submaximal exertion estimation error. * denotes a significant difference ($p < 0.05$) between levels of the replication factors.

4.1.2 Effect of Experiment

The experiment main effect was statistically significant ($F(1,514) = 45.03$, $p < 0.001$), but the two-way interaction effects of experiment * replication ($F(1,514) = 11.63$, $p = 0.001$) and experiment * force level ($F(2,514) = 11.01$, $p < 0.001$) were also statistically significant. Figure 4.4 illustrates the main effect of experiment, with experiment A being significantly greater that experiment B ($p < 0.0001$), but this effect is clearly influenced by the experiment * replication interaction effect described in Figure 4.2 previously.

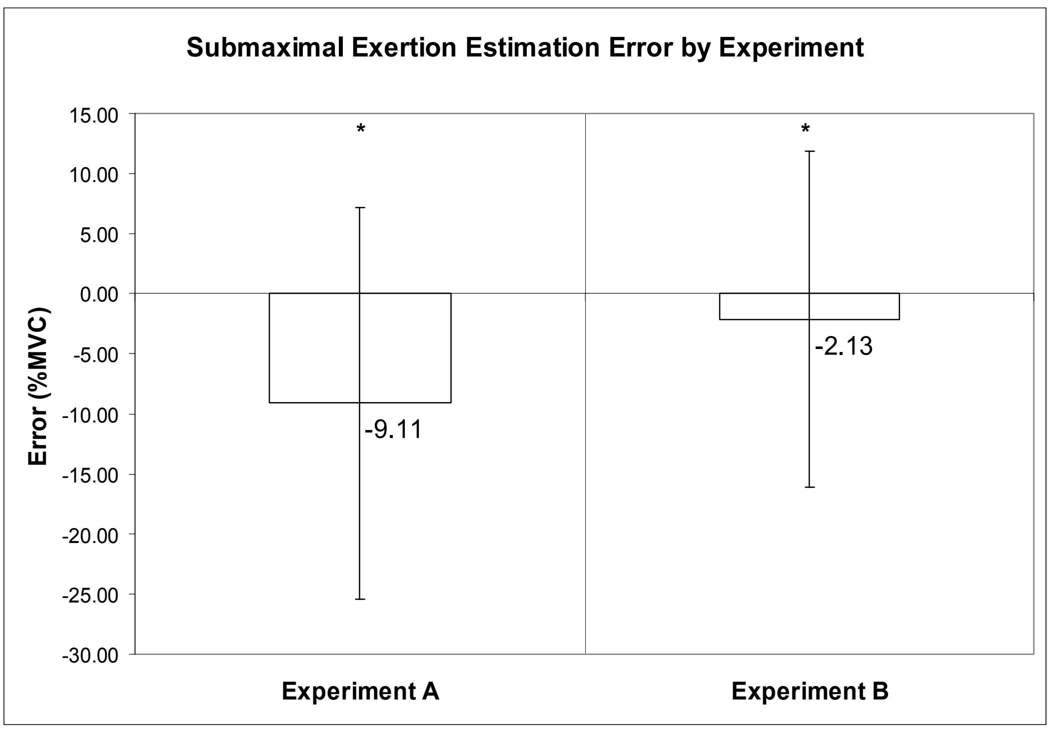


Figure 4.4 Main effect of experiment on submaximal exertion estimation error. The number of *'s represent significant differences ($p < 0.05$) among conditions.

The experiment * force level interaction effect can be seen in Figure 4.5. This interaction effect contains significant differences between experiments at both the medium ($p = 0.0038$) and high force levels ($p < 0.0001$), but not for the low force level (p

= 0.9999). This interaction preserves the trend from the experiment * replication interaction, as each force level has more error for experiment A than for experiment B.

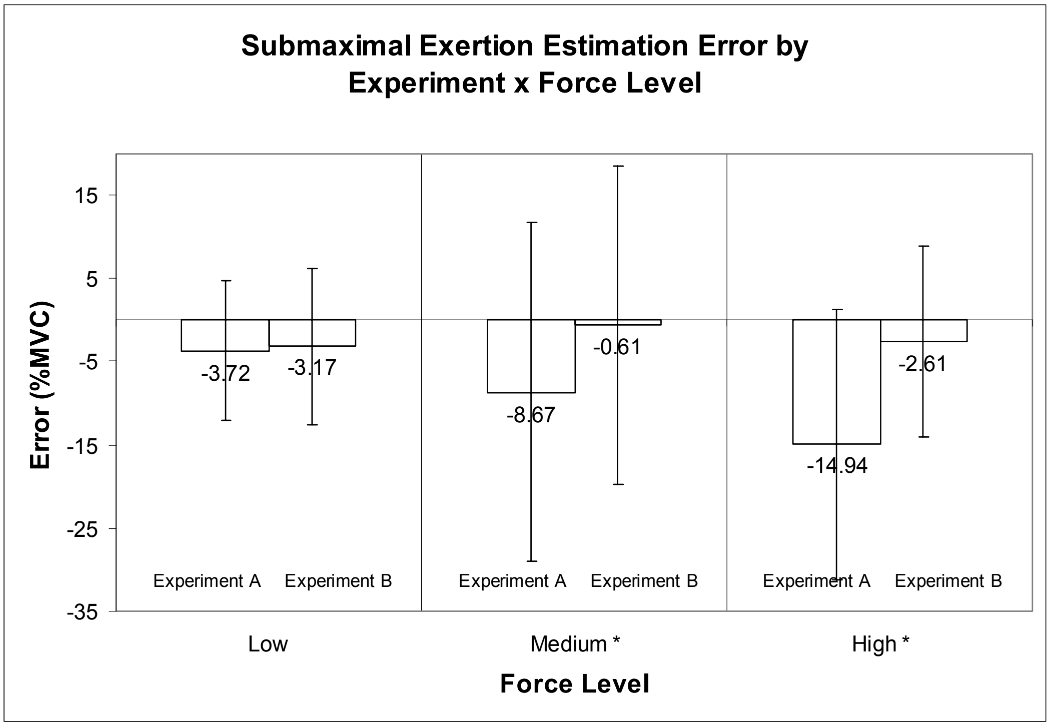


Figure 4.5 Interaction effect of experiment and force level on submaximal exertion estimation error. * denotes a significant difference (p < 0.05) between levels of the experimental factor.

4.1.3 Effect of Force Level

The main effect of force level is illustrated in Figure 4.6. This effect was statistically significant ($F(2,514) = 9.71$, $p < 0.001$), with the high force being significantly greater than the low ($p = 0.0001$) and medium ($p = 0.0032$) levels. However, again it is necessary to interpret the effect of force in light of its significant interaction effects, where force level * replication ($F(2,514) = 6.54$, $p = 0.002$) (Figure 4.3) and force level * experiment ($F(2,514) = 11.01$, $p < 0.001$) were significant (Figure 4.5).

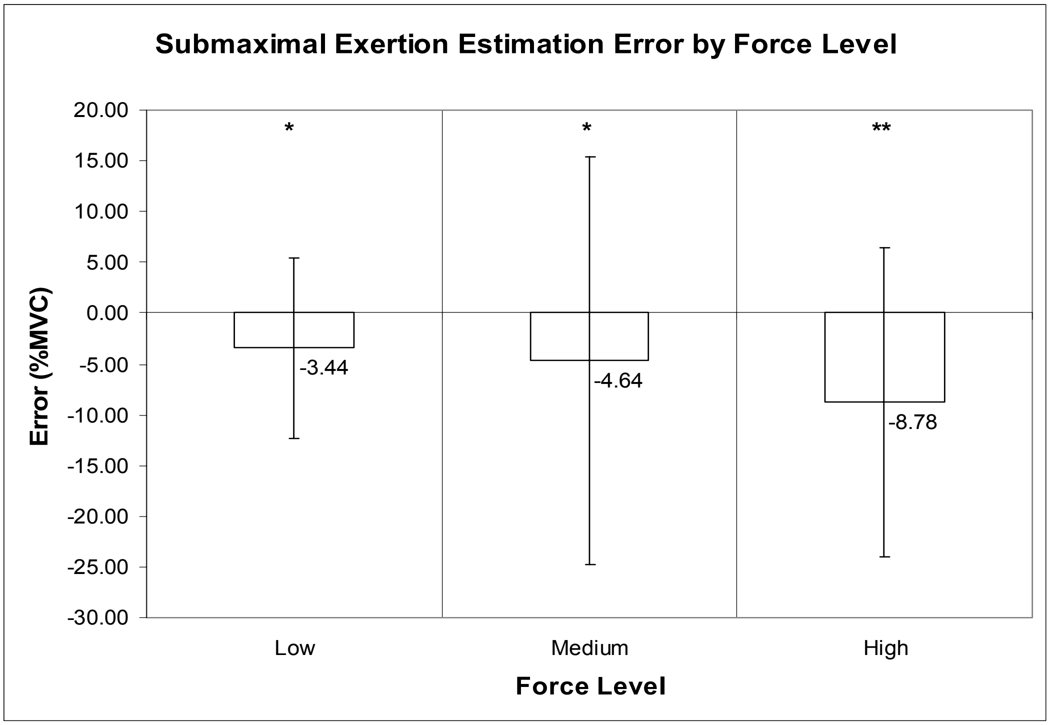


Figure 4.6 Main effect of force level on submaximal exertion estimation error. The number of *'s represent significant differences ($p < 0.05$) among conditions.

The force level * experiment interaction can be seen in Figure 4.5 and was described previously. Here, replication 2 of experiment A appears to be driving the error for all force levels, as experiment A has greater error than experiment B across force levels, but is only statistically significant for the medium ($p = 0.0038$) and high ($p < 0.0001$) force levels. The large error at the high force condition of experiment A (-14.94 % MVC) also appears to be driving the main effect, as the high force was significantly different from the other levels.

The force level * replication interaction can be seen in Figure 4.3 and was described previously. The only significant difference occurs at the medium force level, where replication 2 is significantly different than replication 1 ($p = 0.0008$).

4.2 Fatigue Perception

4.2.1 Effect of Fatiguing Task Force Level and Order on Fatigued Strength Estimate

As described earlier, following the first set of exertion estimates in experiment A, subjects performed a series of three fatiguing tasks after which they were asked to "Please estimate, as a percentage of your initial maximum prior to the fatigue task, your current maximum ability." The fatiguing tasks lasted for one minute or until the subject could no longer maintain the force within 10% of the target force. The fatigued strength percentage was then calculated from this estimate following a MVC test immediately after the strength estimation and can be seen in formula 4.1.

$$MVC_{After} \,/\, MVC_{Before} = \textit{Fatigued Strength Percentage} \qquad 4.1$$

This fatigued strength percentage was then subtracted from the estimate of current strength percentage to get the error in fatigued strength estimate and can be seen in formula 4.2.

$$\begin{array}{c} \textit{Estimated Strength} \\ \textit{Percentage} \end{array} - \begin{array}{c} \textit{Fatigued Strength} \\ \textit{Percentage} \end{array} \quad \begin{array}{c} \textit{Error in Fatigued} \\ \textit{Strength Estimate} \end{array} \qquad 4.2$$

A two-factor analysis of variance was then performed on the data to ascertain the significance of the fatiguing task force (25%, 50%, or 75% MVC) and order (1^{st}, 2^{nd}, or 3^{rd}) on the fatigued strength estimation error (estimated strength %MVC – actual strength %MVC). This analysis of variance can be seen in Table 4.3 and in Appendix D.

Table 4.3 Two-factor analysis of variance of fatigued strength estimation error.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Subject	14	3373.87	2154.64	153.90	2.10	0.057
Order	2	673.73	124.83	62.42	0.85	0.440
Fatiguing Task Force	2	961.14	1092.25	546.13	7.47	0.003
Order*Fatiguing Task Force	4	725.24	725.24	181.31	2.48	0.074
Error	22	1609.23	1609.23	73.15		
Total	44	7343.20				

This analysis of variance showed that the main effect of the force level on the accuracy of the fatigued strength estimate was significant (F(2,22) = 7.47, p = .003) The main effect of the variable fatiguing task force level can be seen in Figure 4.7. For the main effect of fatiguing task force, the 75% MVC level was significantly different from the 25% MVC level (p = .0371), as was the 50% MVC level (p = .0039). However, the 75% level and 50% level were not significantly different from each other (p = 0.6409).

The interaction fatiguing task force * order (F(4,22) = 2.48, p = 0.074), as well as the main effect of order, were not significant (F(2,22) = 0.85, p = .440). The main effect of the variable order can be seen in Figure 4.8. No levels were significantly different for the main effect of order at the α = 0.05 level, although an increase in error was observed as order increased.

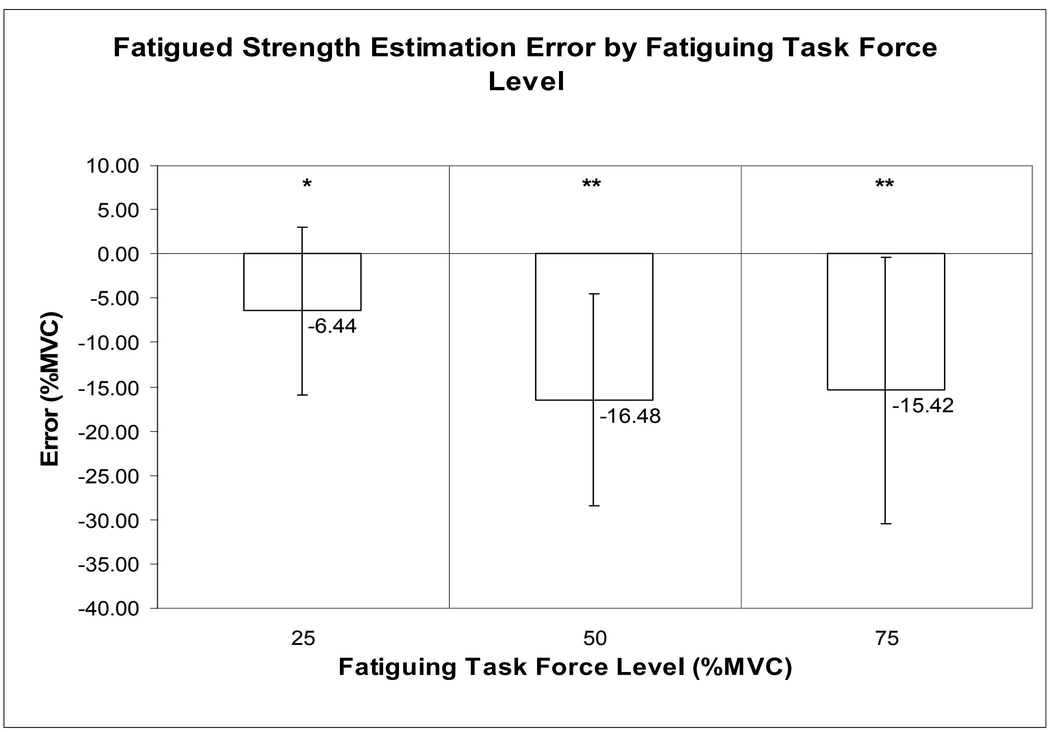


Figure 4.7 Main effect plot of fatiguing task force level on fatigued strength estimation error. The number of *'s represent significant differences (p < 0.05) among conditions.

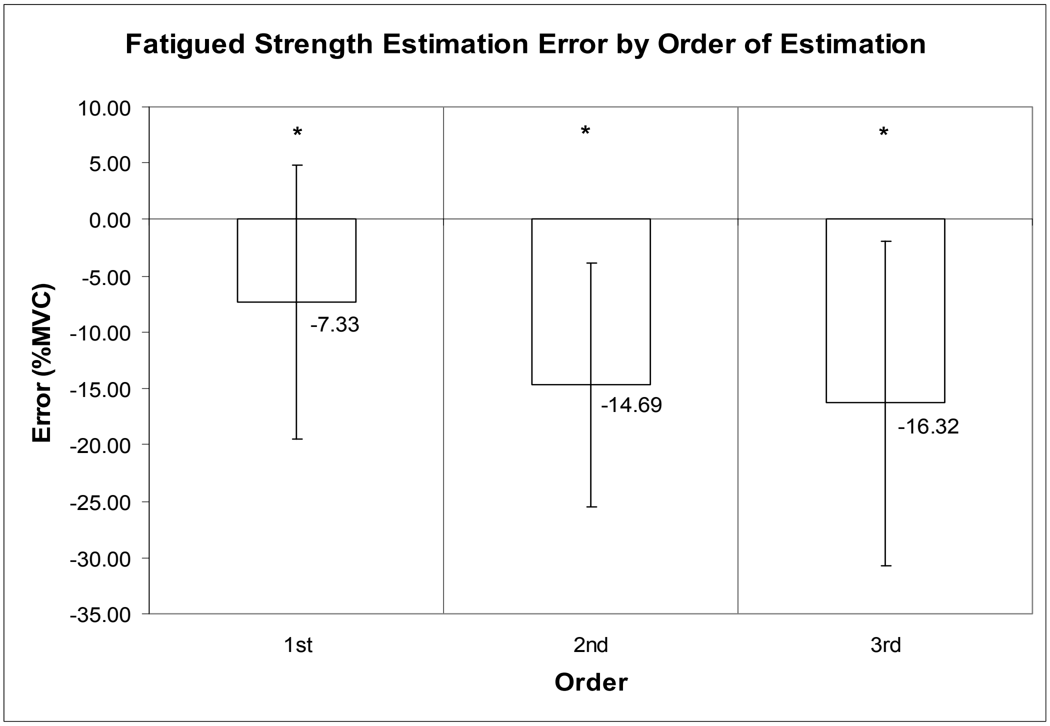


Figure 4.8 Main effect of order of estimation on fatigued strength estimation error. The number of *'s represent significant differences ($p < 0.05$) among conditions.

4.2.2 Effects of Fatiguing Task Force and Order on Perceived Discomfort

As described earlier, following the first set of exertion estimates in experiment A, subjects performed a series of three fatiguing tasks where they were asked to estimate their strength after performing a fatiguing task. Along with this strength estimate, subjects were asked to estimate their discomfort while performing the task using the Borg CR-10 scale (Borg, 1990). The scale used can be seen in Appendix B.

A two-factor analysis of variance was then performed to determine the significance of the fatiguing task force (25, 50, or 75% MVC) and order (1^{st}, 2^{nd}, or 3^{rd}) on the perceived discomfort of the task. The analysis of variance results can be seen in Table 4.4 and in Appendix E.

Table 4.4 Two-factor analysis of variance of perceived discomfort of fatiguing task.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Subject	14	101.495	80.629	5.759	7.51	0.000
Order	2	15.024	4.495	2.248	2.93	0.074
Fatiguing Task Force	2	116.258	95.267	47.634	62.14	0.000
Order*Fatiguing Task Force	4	4.947	4.947	1.237	1.61	0.206
Error	22	16.864	16.864	0.767		
Total	44	254.588				

This analysis of variance showed that the main effect of the variable fatiguing task force on the perceived discomfort value was significant ($F(2,22) = 62.14$, $p < 0.001$). The main effect is presented in Figure 4.9. The mean value for perceived discomfort was significantly higher at the 50% level than at the 25% level and significantly higher at the 75% level than at the 50% level and the 25% level. As a trend, perceived discomfort increased almost linearly as the fatiguing task force increased.

The variable order was not significant as part of the interaction in the fatiguing task force * order interaction effect ($F(4,22) = 1.61$, $p = 0.206$) or as a main effect ($F(2,22) = 2.93$, $p = .074$). The main effect plot can be seen in Figure 4.10. No statistically significant differences occurred between the levels of order.

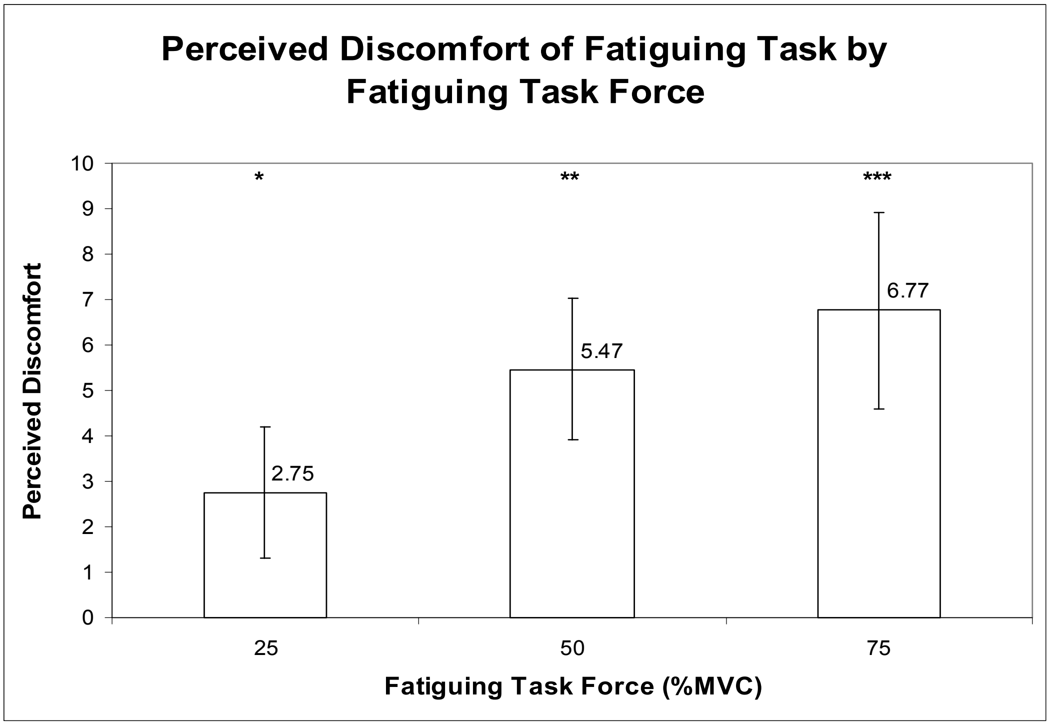


Figure 4.9 Main effect plot of fatiguing task force on perceived discomfort of fatiguing task. The number of *'s represent significant differences ($p < 0.05$) among conditions.

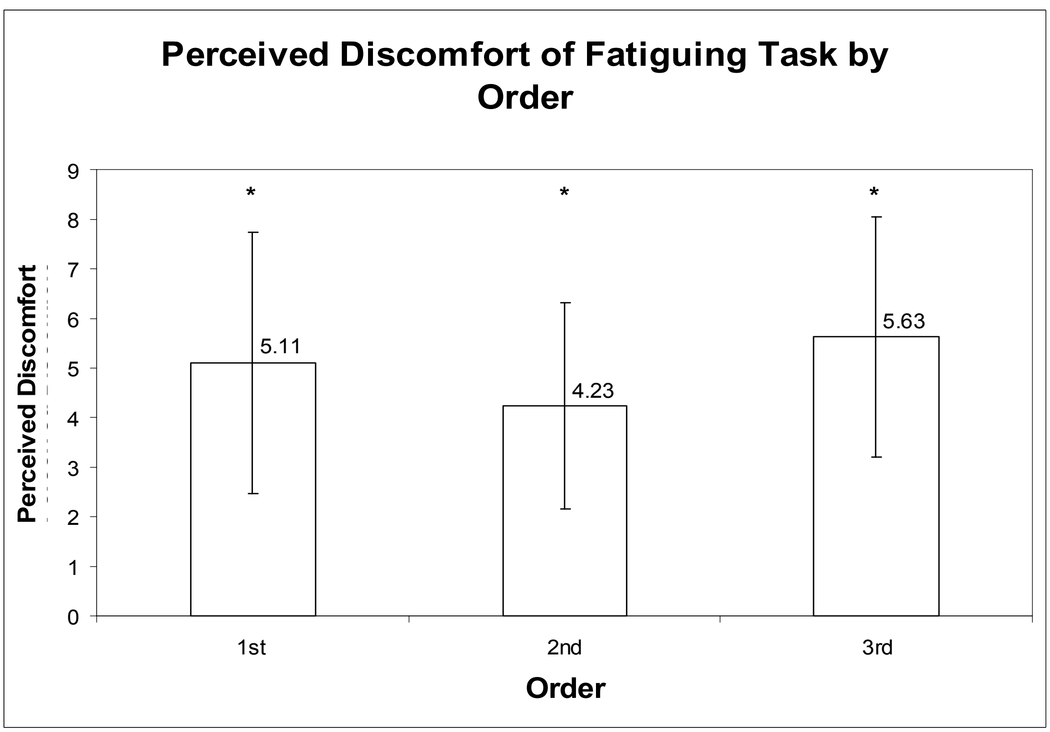


Figure 4.10 Main effect plot of order on perceived discomfort of fatiguing task. The letters represent significant differences ($p < 0.05$) among conditions.

4.2.3 Relationship between Perceived Discomfort, Error, and Strength Loss in Fatigued Strength Estimate

Following the analysis of variance of both the error in the fatigued strength estimate and the perceived discomfort in the fatiguing task, these two dependent variables were examined along with the strength loss to determine their relationship.

4.2.3.1 Fatigued Strength Estimate and Perceived Discomfort

It would be logical if the fatigued strength estimation error had a directly proportional relationship with perceived discomfort, where the harder the subject perceived the task to be (higher perceived discomfort), the greater their error would be when estimating their fatigued strength. Looking at the graph of perceived discomfort vs. fatigued strength estimation error (Figure 4.11), a weak linear trend is present. This trend suggests a slight increase in underestimation as the task felt more uncomfortable.

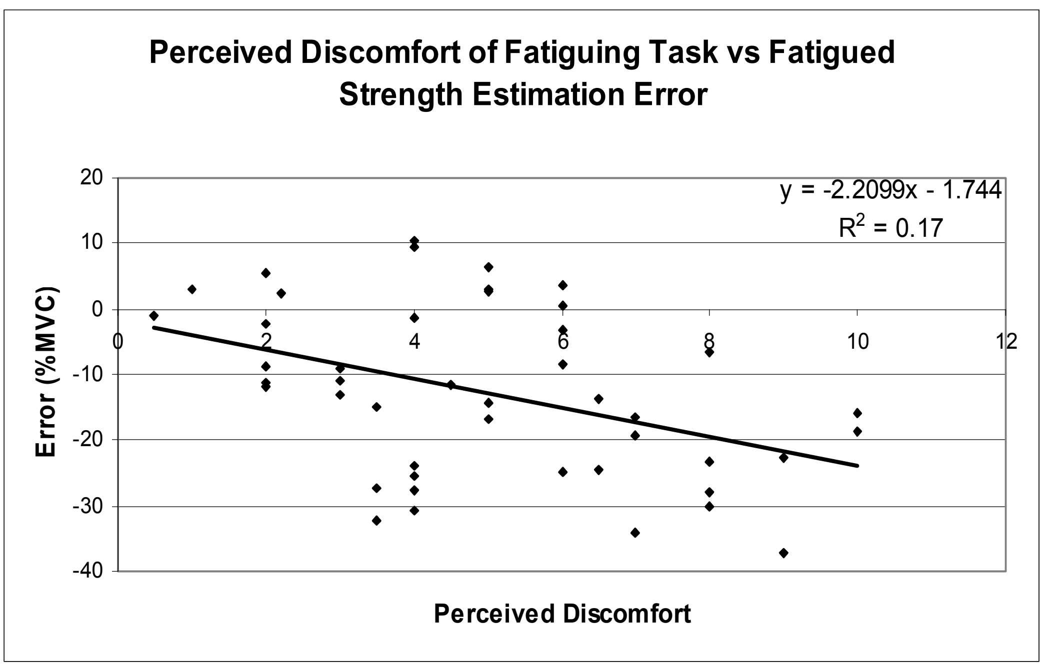


Figure 4.11 Graph of perceived discomfort of fatiguing task vs. fatigued strength estimation error with trendline.

4.2.3.2 Fatigued Strength Estimation Error, Perceived Discomfort, and Strength Loss

The actual strength loss of the subjects was monitored as a byproduct of determining the error in the fatigued strength estimate. However, the actual strength loss is important in knowing exactly how fatigued the subject was when they estimated their strength. Prior to performing the experiment, no expected values for the strength loss were determined. Instead, the generalization that the high force level (75% MVC) would create more strength loss came from the fact that subjects were not expected to be able to maintain that force for a full minute while for the medium (50% MVC) and low (25% MVC) force levels, subjects were. This was based on the Rohmert curve (Rohmert, 1960), which specified maximum endurance times for exertions, where 75% MVC equates to about a 45 second maximum endurance time for sustained static exertion, while 50% MVC equates to approximately 1.25 minutes and 25% MVC to approximately 3.5 minutes, respectively. This is illustrated in Figure 3.6.

Data for the strength loss was plotted against both the fatigued strength estimation error (Figure 4.12) and the perceived discomfort (Figure 4.13). A regression approach was used to analyze the effect of strength loss on both the fatigued strength estimation error and the perceived discomfort and can be seen in Appendix G. Strength Loss was not a significant factor in determining the fatigued strength estimation error ($F(1,43) = 2.24$, $p = 0.142$). In Figure 4.12, the randomness of the distribution serves to highlight this lack of significance. However, Strength Loss was a significant factor in determining the perceived discomfort ($F(1,43) = 7.48$, $p = 0.009$). This relationship explained approximately 14.8% of the variability of the data.

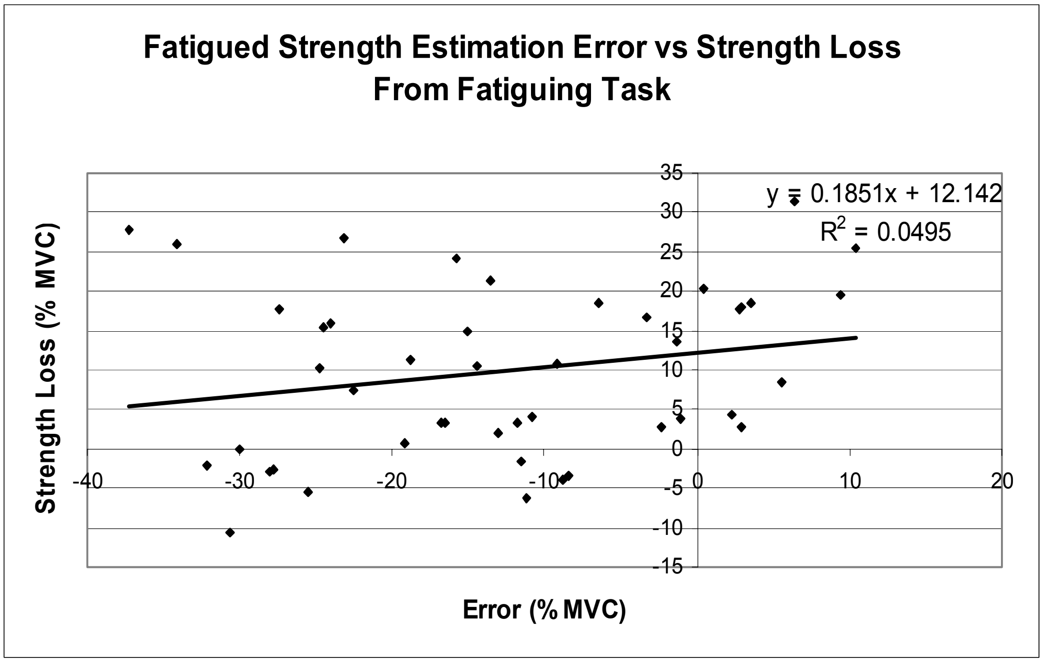


Figure 4.12 Graph of fatigued strength estimation error vs. strength loss from fatiguing task.

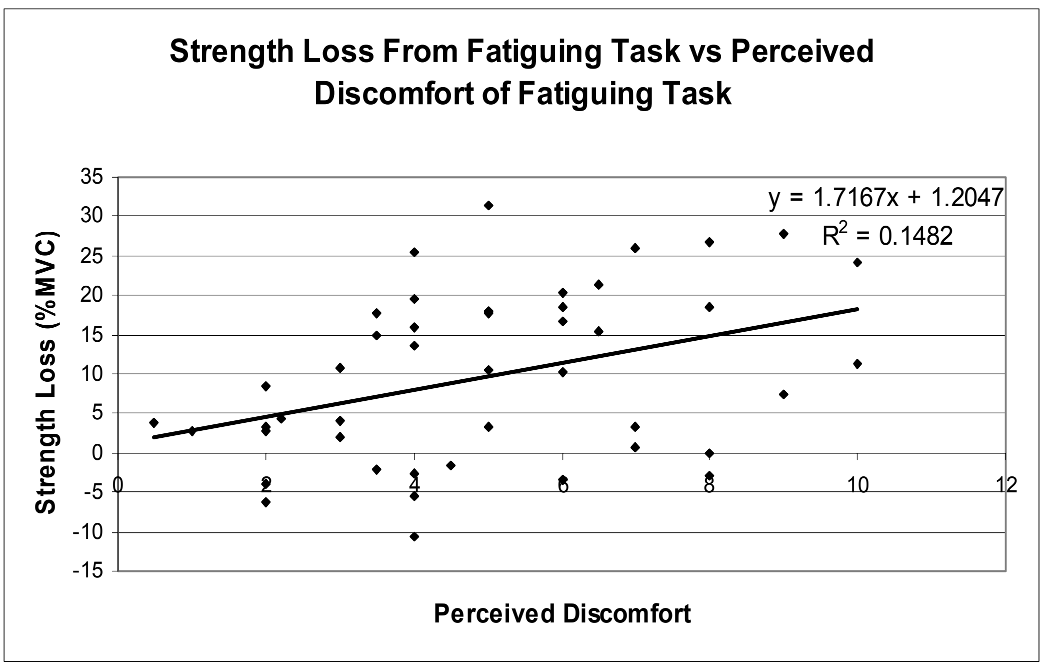


Figure 4.13 Graph of perceived discomfort of fatiguing task vs. strength loss from fatiguing task with trendline.

4.2.3.3 Strength Loss and Fatiguing Task Force

Since strength loss was not a significant factor in determining fatigued strength estimation error, yet fatiguing task force level was, it became necessary to examine the relationship between strength loss and fatiguing task force since these factors were expected to be directly related. An analysis of variance was conducted on strength loss and can be seen in Table 4.5 and Appendix F.

Table 4.5 Two-factor analysis of variance of strength loss caused by fatigue task.

Source	DF	Seq. SS	Adj. SS	Adj. MS	F	P
Subject	14	0.021	0.228	0.016	2.71	0.018
Order	2	0.041	0.039	0.020	3.27	0.057
Fatiguing Task Force	2	0.086	0.052	0.026	2.71	0.018
Order*Fatiguing Task Force	4	0.034	0.034	0.008	1.4	0.266
Error	22	0.132	0.132	0.006		
Total	44	0.506				

The main effect of fatiguing task force level was found to be significant ($F(2,22) = 4.32$, $p = 0.026$). Figure 4.15 shows the main effect plot of fatiguing task force on strength loss, where it is apparent that strength loss increased nearly linearly as the level of the fatiguing task force increased. The 75% fatiguing task force level was significantly different than the 25% force level ($p = 0.0240$). This is important as it verifies that there was a direct relationship between induced fatigue (strength loss) and the fatiguing task force, even if the increase in strength loss at each level was not highly significant.

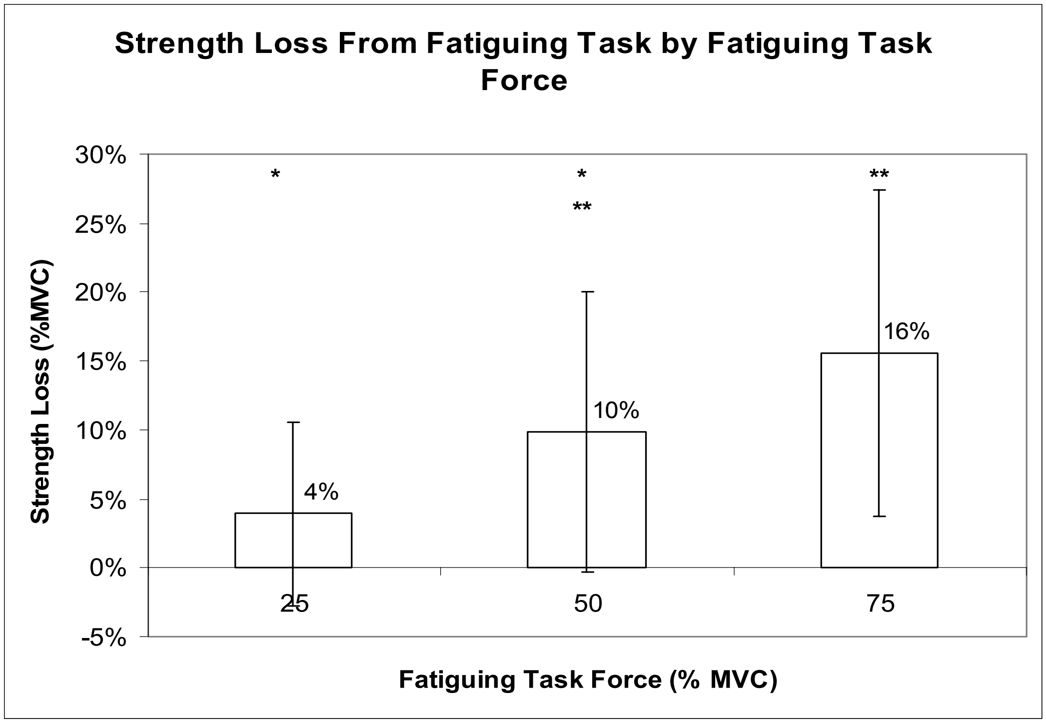


Figure 4.14 Main effect plot of fatiguing task force on strength loss from fatiguing task force. The number of *'s represent significant differences ($p < 0.05$) between conditions.

Section 5

Discussion

5.1 Error in Submaximal Exertion Estimation

Because psychophysical magnitude estimation offers workplace ergonomics with a simple method of force estimation, the objectives of this study were to evaluate the effects of force and fatigue on the accuracy of estimations of exertion intensity as well as evaluate the repeatability of psychophysical magnitude estimation. Subjects performed three estimations at each of the three force levels (low, medium, high) in random order for two replications in each of two separate experiments. Replication 1 followed the initial MVC test, while replication 2 was performed at the end of the experiment. The two separate experiments were performed one week apart to assess the repeatability of the estimations. In between replications of experiment A, subjects performed three fatiguing tasks, each at different exertion levels which were assumed to produce different levels of fatigue.

Overall for the experiment, exertion estimation error was on average -5.62 % MVC. So on average, subjects were within approximately 6 % of their maximum strength when estimating forces of unknown magnitudes. It is interesting to note that subjects in this study tended to underestimate their exertion for virtually all conditions, as shown by the negative mean estimation error (the exceptions were experiment B, replication 1, medium force level and experiment B, replication 2, high force where the mean error was positive, see table 4.1). This is directly in line with the findings of Chin (1995), who also found subjects to underestimate across all force levels. However, this contrasts with what was found in other research by Marshall et. al (2004) and Spielholz (2006), who both found that subjects tended to overestimate forces. Based on such mixed results, additional investigation into the issue is needed.

The driving force in the analysis of variance was the interaction between experiment and replication (Figure 4.2). This interaction demonstrates the importance of the influence of fatigue on the exertion estimates. Although nearly all of the main and interaction effects were significant in evaluating error in submaximal exertion estimations, this interaction was the most prominent and the most influential effect of them all. The significance of this interaction (experiment * replication) was expected, as one of the initial hypotheses was that fatigue would negatively influence exertion estimation error.

5.1.1 Repeatability of verbal estimation in submaximal exertion estimations

In order for psychophysical magnitude estimation to be useful in workplace settings, it needs to be reliable. Part of being reliable is the ability to produce the same results under the same conditions. Without an understanding of repeatability, the tool is not as valuable since the results cannot be properly interpreted.

In the absence of fatigue, psychophysical magnitude estimation appears to be repeatable in short term (30 minutes apart) situations since there was no significant difference between replications of experiment B. As explained in section 4.2, the experiment was designed so that subjects would have a 30 minute rest period between replications of experiment B to test the short term repeatability. Force level was not considered in the repeatability discussion since it was not significant in the 3-way interaction experiment * replication * force level (table 4.1) and was clearly driven by fatigue as a main effect and in the 2-way interactions. Experiment B showed no significant change in estimation error between replication 1 and 2 (Figure 4.2). In fact, the change is actually only -0.48 %MVC; an increase in error from -1.89 %MVC (replication 1) to -2.37 % MVC (replication 2). There is a significant change between replications of experiment A, which is due to fatigue. If fatigue did not have an effect on submaximal exertion estimations, experiment A would have been expected to show very similar results to experiment B. This minimal change suggests short term repeatability with psychophysical magnitude estimation.

Psychophysical magnitude estimation appears to be repeatable over relatively short time periods. These findings are in line with that of Wiktorin et. al (1996), who found push and pull forces to be highly reproducible when performed with one hour between tests and Carlsoo (1986), who found subjects to be within 10% of their targeted force when performing several static forces over a short duration.

Psychophysical magnitude estimation also appears to be repeatable in long term situations since there was no significant difference between the first replication for experiments A and B, which were separated by one week.

Force level was not important to the repeatability analysis since it was not significant in the 3-way interaction experiment * replication * force level (table 4.1) and was clearly driven by fatigue as a main effect and in the 2-way interactions. The experiment was designed so that subjects were counterbalanced as to which experiment was performed first (A or B). Therefore, the first replication of each experiment should not be affected by training, which has been shown to improve subject's ability to verbally estimate exertions (Marshall et. al, 2004; Spielholz, 2006). There was no significant difference between replication 1 of experiment A and replication 1 of experiment B (Figure 4.2). Replication 1 of experiment A did show slightly higher errors than replication 1 of experiment B (-5.33, -1.89), but the difference was not significant. If psychophysical magnitude estimation was not repeatable over a long time, a significant difference between replication 1 of experiment A and B would have been seen. These findings are in line with other research which has found psychophysical magnitude estimation to be repeatable over longer time periods, such as one day (Kumar et. al, 1994). Since there was no significant difference between these conditions, it is fair to conclude psychophysical magnitude estimation has good long term repeatability.

The findings of this study support that psychophysical magnitude estimation was repeatable in both short term (30 minutes) and long term (1 week) settings. This not only confirms the original hypothesis, but also helps to validate psychophysical magnitude estimation as an acceptable tool for industrial applications of workplace ergonomics. Practitioners can trust that there will be no significant difference in psychophysical magnitude estimations due to the time between the estimations. A practitioner can feel safe that when a group of subjects perform psychophysical magnitude estimations, the same group would not give significantly different estimates at another time later in the week assuming the conditions were the same.

5.1.2 Effect of fatigue on psychophysical magnitude estimation

Fatigue appears to have a significantly detrimental effect on psychophysical magnitude estimation. Three fatigue tasks were performed between replications 1 and 2 of experiment A. Following the first two tasks, subjects were given a five minute recovery break in order to allow them to recover from the fatiguing tasks. Following the third fatiguing task, subjects were not given a recovery period, instead immediately beginning replication 2 of the exertion estimates. The average fatigue at this point can be taken from the average strength loss which was 13 %MVC (table 4.3), indicating that subjects were somewhat fatigued.

This fatigue caused the exertion estimates seen in replication 2 for experiment A to contain significantly more error than those same estimates in replication 1 of experiment A (Figure 4.2), which was true across all force levels. In fact, the magnitude of the increase in error was such (-7.56% MVC) that it alone was greater than the error in any other replication.

As noted earlier, subjects underestimated weights under most conditions during this experiment. This is especially true for the estimations made under fatigue. The significant increase in estimation error was actually an increase from a relatively constant underestimate, creating a larger underestimate further from the true force. For example, a 6% MVC underestimate was compounded with another 6% error due to fatigue, creating a 12% MVC underestimate. This is consistent with the findings of Deeb (1999), who found that subjects underestimated forces when fatigued.

The reasons for this increase in estimation error due to fatigue are not immediately clear. At some point during the information transfer, the presence of fatigue (loss of strength) found in the muscles is lost or distorted, resulting in the subject believing they are stronger than they actually are at that time. Whether this happens somewhere in the muscles, where an actual instantaneous strength is not determined, or in the nervous system, where the understanding of an actual instantaneous strength is lost or not processed is not answered by this experiment.

This knowledge that fatigue significantly increases the error of psychophysical magnitude estimation validates the original hypothesis and is important for practitioners in the field. Any use of psychophysical magnitude estimation should be performed by employees at the beginning of their shift prior to the onset of fatigue from normal work tasks. Additionally, any estimates of work task difficulty made in the presence of fatigue must have their validity questioned. So based on these results, if a subject was estimating their exertion on a task which required 75% MVC of their strength, they would estimate on average for the task to require approximately 72% MVC if they were not fatigued. However, if the subject was greatly fatigued, they would estimate the same task to require approximately 62% MVC, which is vastly different from what the task actually requires.

5.1.3 Effects of force level on psychophysical magnitude estimation

Force level was broken down to three levels in this experiment: low (10, 15, & 20 %MVC), medium (40, 50, & 60 %MVC), and high (75, 85, & 90 %MVC). This study found force level to be significant not only as a main effect, but also in interactions with experiment and replication (Table 4.2). This is consistent with other research, such as that performed by Marshall et. al (2004) and Deeb (1999), which also found estimation error to be dependent on force level.

As stated in section 4, the significance of the interaction effects was most likely driven by the fatigue seen in replication 2 of experiment A. The magnitude of the increase in error was powerful enough to cause the interactions to appear significant. However, this may not have been the case with the main effect, since the high force level was significantly different than the medium or low force level. Additionally, it is important to note that in table 4.1, half (3 out of 6) of the conditions which were statistically different than zero were at the high force level. The condition with the least estimation error also happens to occur at the high force level (Table 4.1). Of the four high error conditions, three of them are the largest in their respective replication, while one is the smallest (Table 4.1). Although this highlights the significance of the high force level, it does not explain the discrepancy, and thus should be researched further in future studies.

The increase in error at high force levels found in this study should aid practitioners of industrial ergonomics in the field by allowing them to trust the results of low and medium force levels more conclusively. However, the discrepancy in increased error at the high force level still needs to be investigated further before any conclusions can be drawn.

This study found a higher variability in midrange exertions (standard deviation = 17.53%) than for low (standard deviation = 12.63%) or high (standard deviation = 16.24%). This is in agreement with the findings of Fairfax et. al (1995), and Marshall et. al (2004) who also found that midrange submaximal estimations had a higher variability than those at the extremes. This increase in variability can be explained by the increased room for error found in the midrange exertions. For midrange exertions, subjects could under or over estimate by more because they were unbounded, unlike the low (bounded by 0) and high (bounded by 100) exertions.

5.2 Fatigue Perception

In between replications of experiment A, subjects performed three fatiguing tasks, each at different exertion levels which were assumed to produce different levels of fatigue based on the Rohmert curve (Figure 3.6). By assessing fatigue level only by physical strength loss, this was for the most part true as subjects lost significantly more strength at the higher level than the lower (Figure 4.15). Following each of these fatiguing tasks, subjects estimated their strength at that time as a percentage of their strength before the task began. Along with the estimate, subjects also estimated their perceived discomfort of performing the fatiguing task.

5.2.1 Error in Fatigued Strength Estimate

The hypothesis being examined by this area of the study was that subjects were unaware of their fatigue level and thus would be unaware of their fatigued strength as it changes from fully rested to fatigued. The results from section 4.3.1 suggest that subjects are indeed less aware of their fatigued strength than they are of other exertions, with a mean error of -12.78% MVC, compared to a mean error of -5.62% MVC for exertion estimates. However, since the fatigued strength estimate is an estimate of maximum strength loss, it is not really the same task as the submaximal exertion estimates performed and the comparison of the two is not that meaningful.

The fact that the error is negative signifies that subjects' estimates of their fatigued strength were on average below their actual strength. This means that following the fatiguing task, subjects thought they were weaker than they actually were. This is in line with the results from the exertion estimates performed while fatigued, where subjects underestimate forces by significantly more than when they were not fatigued. This could be a margin of safety; since the body is unable to determine the actual capability of the muscles, it chooses a lower, safer estimate in order to avoid injuries from overexertion.

In section 4.3.1, the order in which the fatiguing tasks were performed was found to be insignificant. Since the fatigue experiment was designed with both a five minute rest period between each task and since the tasks were performed in a random order each time, this was expected. However, even though the levels are not significantly different within order, there is an increase in error seen from the 1st task to the 3rd task. This error could be caused by the five minute rest period not being sufficient for total recovery from the previous fatiguing task. Even though subjects were told prior to each fatigued strength estimate to estimate based on their maximum strength before the most recent fatiguing task, if the five minute recovery period was indeed insufficient it is possible they carried over some of the perceived weakness from the previous task, increasing their error on the subsequent estimates. Since the main effect of order as well as the interaction effect between order and fatiguing task force were not significant, it is doubtful this impacted the results substantially.

An interesting finding in the results was that even though the lowest fatiguing task force (25% MVC) produced the lowest mean error which was significantly different than both the medium (50% MVC) and high (75% MVC) fatiguing task force, there was no significant difference between error at the medium and high fatiguing task force levels. In fact, the medium 50% fatiguing task level actually had a larger mean error than the 75% fatiguing task level (Figure 4.7). So although strength loss increased almost linearly as the fatiguing task force increased (Figure 4.15), the error in the strength estimate seemed to level off after the medium 50% fatiguing task level. This suggests that the amount of fatigue present may not have been the primary cause of error.

It appears that the error in the fatigued strength estimate was independent of the amount of fatigue or strength loss and is instead based on the simple presence of fatigue. This is supported by Figure 4.12 which shows no clear pattern in the plot of fatigue strength estimation error vs. strength loss. If the error of the fatigued strength estimate increased with the amount of fatigue present, then there should have been some pattern between strength loss and fatigued strength estimation error. However, the lack of this pattern suggests that error increases until it hits some sort of fatigue threshold where the error levels out. More research will need to be done on this concept of a fatigue threshold.

Even though the fatigued strength estimation did not increase as the fatiguing task force increased, the variability in the estimates did, although not significantly (Figure 4.7). The standard deviation increased very nearly linearly as the fatiguing task force increased, with the maximum of 15.02 % occurring at the 75% fatiguing task force. Even though the error of the fatigued strength estimate did not necessarily increase with the amount of fatigue present, the precision of the estimate certainly did decrease inversely with the amount of fatigue.

Some subjects were aware that their muscles were being fatigued and becoming weaker, as suggested by Sjogaard (1986), Bystrom & Fransson-Hall (1994), and Bystrom & Kilbom (1990). However, subjects were not accurately aware of the amount of strength loss due to the fatigue, only that they were generally becoming weaker. This is important to practitioners in the field since it shows that subjects can not be expected to be accurately aware of their maximum strength at times when they are fatigued. The underestimation of the results should quell fears that this lack of awareness will lead to injuries, as it seems the body may be compensating for its inability to accurately predict its current strength by lowering strength expectations.

5.2.2. Perceived Discomfort of Fatiguing Task

After performing the fatiguing task, subjects were asked to estimate their perceived discomfort at performing the fatiguing task on the Borg CR-10 scale (Borg, 1990). It seems reasonable that a higher fatiguing task force level would cause more strength loss and a higher perceived discomfort, which is seen in the results (Figure 4.9; Figure 4.13). As the tasks become more physiologically difficult (higher fatiguing task force), subjects felt more uncomfortable performing them. This was exemplified by the high (75% MVC) fatiguing task force, where subjects were not necessarily able to complete the one minute task because it was designed to be above their maximum endurance (Figure 3.6). Since the one minute duration was unobtainable, subjects logically would feel more discomfort as they reached a point of exhaustion and had to stop short of the one minute goal. In addition to the significant increase in perceived discomfort across fatiguing force levels, variability increased across fatiguing force levels, although not significantly. The increase in variability of perceived discomfort follows the same pattern as the variability of the strength estimate error, where it increases from low to high fatiguing task force.

It is also logical that perceived discomfort would be a predictor of strength estimation error, which it was, although not strongly (Figure 4.11). Tasks with higher discomfort will involve more background noise within the brain for the person trying to produce the exertion estimate. This may be enough to cloud the understanding of the strength lost while performing the task.

The correlation between perceived discomfort and strength estimation error, albeit weak, is important for practitioners of industrial ergonomics to know. Work tasks that are perceived as uncomfortable can cloud a workers ability to determine their strength after the task, possibly putting them at higher risk for injuries.

5.3 Limitations

Certain factors affected the results of this study, such as the narrow definition of fatigue and the use of only one task. Some of the most relevant causes of errors and limitations are listed below:

- Fatigue was defined for this study in purely physical terms through strength loss. However, a key component to a complete understanding of fatigue is mental fatigue, which can amplify the effects of physical fatigue. Additionally, no biophysical measurements were taken to further evaluate the presence of fatigue.
- The subject population was composed entirely of college students with minimal knowledge of the work simulator machine and psychophysical magnitude estimation. More experienced employees may produce different results with tasks they are more familiar with.
- This study only considered a power grip task. However, previous research has found no significant difference between different tasks as long as they utilized only the forearm and upper arm muscles (Marshall et. al, 2004),
- The time frame of each experiment was approximately 45 minutes with the fatiguing task a 1 minute static exercise. Different time frames may lead to different results on the repeatability of psychophysical magnitude estimation.

Also, the one minute maximum of the fatiguing task did not allow for any analysis of how the accuracy of the fatigued strength estimate would vary as the fatigue builds in the muscles.

5.4 Future Research

Based on the knowledge gained from this study, several suggestions are made for future research:

- Increase the size and diversity of the sample used. This study used a sample size of 15 subjects, although a larger sample would help to reduce the variability. Additionally, a sample consisting of subjects who actually perform tasks like what is required by the study on a regular basis may provide more validity than a random student population.
- Enhance the perception of fatigue for subjects to include both mental and physical fatigue. This study was limited to only examining physical fatigue due to time constraints, however a longer experimental time frame may allow the study to examine the effects of physical and mental fatigue on psychophysical magnitude estimation.
- Use multiple time frames in the analysis of psychophysical magnitude estimations repeatability. This study found psychophysical magnitude estimation to be repeatable over both 30 minute and 1 week time periods, however other time periods were left unchecked.
- Analyze the error in fatigue estimation over time. This study was limited in that it only evaluated the estimate after a (maximum of) one minute fatiguing task. A

longer fatiguing task could perhaps test fatigued strength estimates at multiple points as fatigue is accumulating and the muscles are weakening.

Section 6

Conclusion

This study investigated the effect of fatigue on the accuracy and repeatability of psychophysical magnitude estimation. In addition, the accuracy with which subjects could estimate their fatigue by strength estimation was examined. A total of 15 subjects performed two approximately 45 minute experiments separated by one weeks time.

The main finding of this study is that fatigue has a significantly detrimental effect on submaximal exertion estimation. Subjects that estimated submaximal exertions in the presence of fatigue underestimated by an average of 7.56% MVC more than when not fatigued.

Psychophysical magnitude estimation was found to be repeatable when subjects performed submaximal exertion estimates without fatigue. In both short term (30 minute) and long term (1 week) settings, subjects were able to estimate submaximal exertions with no significant differences between the errors.

Subjects were not able to accurately estimate the level of their maximum strength (compared to their original maximum) when fatigued. After performing a fatiguing task, subjects were asked to estimate their current maximum strength as a percentage of their unfatigued maximum strength. On average, subjects underestimated their fatigued maximum strength by 12.87% MVC.

This study provides useful information for practitioners of industrial ergonomics who use psychophysical magnitude estimation as an easy, inexpensive method of measuring exertion intensity in the field. In order for the results of verbal exertion estimations to be accepted, practitioners need to ensure the subjects are not fatigued. Practitioners can be confident in the repeatability of psychophysical magnitude estimation assuming the subject is not fatigued. Subjects should also not be expected to have an awareness of how much strength they had lost due to fatigue.

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Appendix A: Informed Consent Form

Rochester Institute of Technology

INFORMED CONSENT FORM

Verbal Estimation Of Exertion During Hand Grip Task

Investigators: Dr. Matthew Marshall and Matthew Klosner

The purpose of the study in which you are considering to participate is to determine the effects of time delay on the accuracy with which subjects are able to verbally estimate perceived exertion during hand grip tasks. In order to participate in this study, you must consent to the following:

INFORMATION

This experiment will involve squeezing the handle on a work simulator for different levels of exertion. We will be assessing your ability to verbally estimate the magnitude of your exertion for a variety of levels.

RISKS

Risks associated with this experiment include muscle soreness and strain. The hand grips required during this experiment will range from a very low force to maximum. These hand grips are no different than what you would be exerting if you were working out at the gym. If you experience any discomfort during the project, immediately inform the experimenter and withdraw from participating.

BENEFITS

This experiment builds on existing research on the accuracy of perceived exertion and what physical and psychological factors affect it. Verbal estimation is a commonly used form of measurement of exertion intensity in industry due to its simplicity and ease. This project will provide researchers and practitioners with a quantified estimate of the "error" associated with verbal estimation. This project will provide the field of ergonomics with valid and effective tools that can be implemented on a widespread basis.

CONFIDENTIALITY

You will be assigned a number code and only the investigators will have access to the list that links your name to the number code you were assigned. Any publication of this work and its results will not refer to you by name.

CONTACT

If you have any questions at any time about the study or the procedures, you may contact the principal investigator, Matthew Marshall, through email at mmmeie@rit.edu or by phone at 585-475-7260.

PARTICPATION

Your participation in this study is completely voluntary; you may decline to participate without penalty. If you decide to participate, you may withdraw from the study at any time without penalty. If you withdraw from the study before data collection is completed, your data may still be used for analysis if applicable. It is understood that neither the experimenter nor the Rochester Institute of Technology shall be held responsible for any injuries which occur during or as a result of the experimentation.

CONSENT

I have read and understand the above information. I have received a copy of this form. I agree to participate in this study.

Subject's signature ____ **Date** _____________

Investigator's signature ____ **Date** _____________

Appendix B: Ratings of Perceived Discomfort

Rating of Perceived Discomfort

Please refer to the following scale to rate your discomfort upon finishing the work task (a decimal number may be used e.g. 3.5)

0	Not at all	
0.5	Very, very light	(just noticeable)
1	Very light	
2	Light	
3	Moderate	
4	Somewhat strong	
5	Strong	(heavy)
6		
7	Very strong	
8		
9		
10	Very, very strong	(almost maximum tolerable)

Appendix C: Analysis of Variance for Submaximal Exertion Estimation

Estimation Error ANOVA

General Linear Model: Error versus Subject, Replication, ...

Factor	Type	Levels	Values
Subject	random	15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
Replication	fixed	2	1, 2
Force level	fixed	3	high, low, medium
Experiment	fixed	2	A, B

Analysis of Variance for Error, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	14	36901.2	36901.2	2635.8	18.15	0.000
Replication	1	2180.0	2180.0	2180.0	15.01	0.000
Force level	2	2820.1	2820.1	1410.0	9.71	0.000
Experiment	1	6580.0	6580.0	6580.0	45.30	0.000
Replication*Force level	2	1900.1	1900.1	950.0	6.54	0.002
Replication*Experiment	1	1688.9	1688.9	1688.9	11.63	0.001
Force level*Experiment	2	3199.0	3199.0	1599.5	11.01	0.000
Replication*Force level*Experiment	2	836.8	836.8	418.4	2.88	0.057
Error	514	74661.0	74661.0	145.3		
Total	539	130767.2				

S = 12.0522   R-Sq = 42.91%   R-Sq(adj) = 40.13%

Main Effects: Replication

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Replication
Replication = 1 subtracted from:

```
Replication   Lower  Center   Upper     +---------+---------+---------+------
2            -6.056  -4.019  -1.981     (---------*---------)
                                        +---------+---------+---------+------
                                     -6.0      -4.0      -2.0       0.0
```

Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Replication
Replication = 1 subtracted from:

Replication	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-4.019	1.037	-3.874	0.0001

Main Effects: Experiment

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Experiment
Experiment = A subtracted from:

```
Experiment  Lower  Center  Upper  ---------+---------+---------+-------
B           4.944   6.981  9.019  (----------------*----------------)
                                  ---------+---------+---------+-------
                                        6.0       7.2       8.4
```

```
Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Experiment
Experiment = A  subtracted from:

            Difference       SE of           Adjusted
Experiment    of Means  Difference  T-Value   P-Value
B                6.981       1.037    6.731    0.0000
```

Main Effects: Force Level

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Force level
Force level = high  subtracted from:

Force
level   Lower  Center  Upper   --+---------+---------+---------+----
low     2.360   5.333  8.307                     (-------*--------)
medium  1.165   4.139  7.112                 (--------*-------)
                               --+---------+---------+---------+----
                              -3.5       0.0       3.5       7.0


Force level = low  subtracted from:

Force
level    Lower  Center  Upper   --+---------+---------+---------+----
medium  -4.168  -1.194  1.779   (--------*-------)
                                --+---------+---------+---------+----
                               -3.5       0.0       3.5       7.0


Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Force level
Force level = high  subtracted from:

Force   Difference       SE of           Adjusted
level     of Means  Difference  T-Value   P-Value
low          5.333       1.270    4.198    0.0001
medium       4.139       1.270    3.258    0.0032


Force level = low  subtracted from:

Force   Difference       SE of           Adjusted
level     of Means  Difference  T-Value   P-Value
medium      -1.194       1.270  -0.9402    0.6148
```

Interaction Effects: Replication x Experiment

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Condition
```

```
Condition = Rep 1, Exp A  subtracted from:

Condition      Lower  Center   Upper  ------+---------+---------+---------+
Rep 1, Exp B   -1.24   3.444   8.125                (---*----)
Rep 2, Exp A  -12.24  -7.556  -2.875      (---*----)
Rep 2, Exp B   -1.72   2.963   7.644               (----*----)
                                      ------+---------+---------+---------+
                                          -10         0        10        20


Condition = Rep 1, Exp B  subtracted from:

Condition      Lower  Center   Upper  ------+---------+---------+---------+
Rep 2, Exp A  -15.68  -11.00  -6.319  (----*----)
Rep 2, Exp B   -5.16   -0.48   4.199             (----*---)
                                      ------+---------+---------+---------+
                                          -10         0        10        20


Condition = Rep 2, Exp A  subtracted from:

Condition     Lower  Center  Upper  ------+---------+---------+---------+
Rep 2, Exp B  5.838   10.52  15.20                       (----*---)
                                    ------+---------+---------+---------+
                                        -10         0        10        20


Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Condition
Condition = Rep 1, Exp A  subtracted from:

              Difference       SE of            Adjusted
Condition       of Means  Difference  T-Value    P-Value
Rep 1, Exp B       3.444       1.824    1.889     0.2328
Rep 2, Exp A      -7.556       1.824   -4.143     0.0002
Rep 2, Exp B       2.963       1.824    1.625     0.3646


Condition = Rep 1, Exp B  subtracted from:

              Difference       SE of            Adjusted
Condition       of Means  Difference  T-Value    P-Value
Rep 2, Exp A      -11.00       1.824   -6.032     0.0000
Rep 2, Exp B       -0.48       1.824   -0.264     0.9936


Condition = Rep 2, Exp A  subtracted from:

              Difference       SE of            Adjusted
Condition       of Means  Difference  T-Value    P-Value
Rep 2, Exp B       10.52       1.824    5.768     0.0000
```

Interaction Effects: Replication x Force Level

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error RF
All Pairwise Comparisons among Levels of Condition RF
Condition RF = Rep 1, High  subtracted from:

Condition RF    Lower   Center   Upper  ------+---------+---------+---------+
Rep 1, Low     -0.025   6.4444  12.914                  (-----*------)
```

```
Rep 1, Medium   2.086   8.5556  15.025                  (------*-----)
Rep 2, High    -6.803  -0.3333   6.136         (------*-----)
Rep 2, Low     -2.581   3.8889  10.359             (------*-----)
Rep 2, Medium  -7.081  -0.6111   5.859         (-----*------)
                                       ------+---------+---------+---------+
                                           -10         0        10        20


Condition RF = Rep 1, Low  subtracted from:

Condition RF    Lower  Center    Upper  ------+---------+---------+---------+
Rep 1, Medium   -4.36   2.111   8.5809              (-----*------)
Rep 2, High    -13.25  -6.778  -0.3080     (-----*------)
Rep 2, Low      -9.03  -2.556   3.9142         (-----*------)
Rep 2, Medium  -13.53  -7.056  -0.5858    (------*-----)
                                        ------+---------+---------+---------+
                                            -10         0        10        20


Condition RF = Rep 1, Medium  subtracted from:

Condition RF    Lower  Center   Upper  ------+---------+---------+---------+
Rep 2, High    -15.36  -8.889  -2.419   (-----*------)
Rep 2, Low     -11.14  -4.667   1.803       (-----*------)
Rep 2, Medium  -15.64  -9.167  -2.697  (------*-----)
                                       ------+---------+---------+---------+
                                           -10         0        10        20


Condition RF = Rep 2, High  subtracted from:

Condition RF    Lower   Center   Upper  ------+---------+---------+---------+
Rep 2, Low     -2.248   4.2222  10.692                (-----*------)
Rep 2, Medium  -6.748  -0.2778   6.192           (------*-----)
                                        ------+---------+---------+---------+
                                            -10         0        10        20


Condition RF = Rep 2, Low  subtracted from:

Condition RF    Lower  Center  Upper  ------+---------+---------+---------+
Rep 2, Medium  -10.97  -4.500  1.970       (-----*------)
                                      ------+---------+---------+---------+
                                          -10         0        10        20


Tukey Simultaneous Tests
Response Variable Error RF
All Pairwise Comparisons among Levels of Condition RF
Condition RF = Rep 1, High  subtracted from:

               Difference       SE of           Adjusted
Condition RF     of Means  Difference  T-Value   P-Value
Rep 1, Low         6.4444       2.270   2.8385    0.0516
Rep 1, Medium      8.5556       2.270   3.7683    0.0023
Rep 2, High       -0.3333       2.270  -0.1468    1.0000
Rep 2, Low         3.8889       2.270   1.7129    0.5231
Rep 2, Medium     -0.6111       2.270  -0.2692    0.9998


Condition RF = Rep 1, Low  subtracted from:

               Difference       SE of           Adjusted
```

```
Condition RF     of Means  Difference  T-Value   P-Value
Rep 1, Medium       2.111       2.270    0.930    0.9389
Rep 2, High        -6.778       2.270   -2.985    0.0337
Rep 2, Low         -2.556       2.270   -1.126    0.8709
Rep 2, Medium      -7.056       2.270   -3.108    0.0232


Condition RF = Rep 1, Medium  subtracted from:

               Difference       SE of            Adjusted
Condition RF     of Means  Difference  T-Value   P-Value
Rep 2, High        -8.889       2.270   -3.915    0.0013
Rep 2, Low         -4.667       2.270   -2.055    0.3110
Rep 2, Medium      -9.167       2.270   -4.037    0.0008


Condition RF = Rep 2, High  subtracted from:

               Difference       SE of            Adjusted
Condition RF     of Means  Difference  T-Value   P-Value
Rep 2, Low         4.2222       2.270   1.8597    0.4273
Rep 2, Medium     -0.2778       2.270  -0.1223    1.0000


Condition RF = Rep 2, Low  subtracted from:

               Difference       SE of            Adjusted
Condition RF     of Means  Difference  T-Value   P-Value
Rep 2, Medium      -4.500       2.270   -1.982    0.3526
```

Interaction Effects: Experiment x Force Level

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error ExF
All Pairwise Comparisons among Levels of Condition ExF
Condition ExF = Exp A, High  subtracted from:

Condition ExF      Lower  Center  Upper   -+---------+---------+---------+-----
Exp A, Low       4.90301  11.222  17.54                  (-----*------)
Exp A, Medium   -0.04144   6.278  12.60             (-----*------)
Exp B, High      6.01412  12.333  18.65                   (-----*------)
Exp B, Low       5.45856  11.778  18.10                  (------*-----)
Exp B, Medium    8.01412  14.333  20.65                      (-----*------)
                                          -+---------+---------+---------+-----
                                         -10         0        10        20


Condition ExF = Exp A, Low  subtracted from:

Condition ExF   Lower  Center  Upper   -+---------+---------+---------+-----
Exp A, Medium  -11.26  -4.944  1.375   (-----*-----)
Exp B, High     -5.21   1.111  7.430         (-----*-----)
Exp B, Low      -5.76   0.556  6.875        (------*-----)
Exp B, Medium   -3.21   3.111  9.430           (-----*-----)
                                       -+---------+---------+---------+-----
                                      -10         0        10        20


Condition ExF = Exp A, Medium  subtracted from:

Condition ExF    Lower  Center  Upper   -+---------+---------+---------+-----
```

```
Exp B, High    -0.2637   6.056  12.37              (-----*-----)
Exp B, Low     -0.8192   5.500  11.82             (------*-----)
Exp B, Medium   1.7363   8.056  14.37                (-----*-----)
                                        -+---------+---------+---------+-----
                                       -10         0        10        20
```

Condition ExF = Exp B, High subtracted from:

```
Condition ExF   Lower   Center  Upper   -+---------+---------+---------+-----
Exp B, Low     -6.875  -0.5556  5.764       (-----*------)
Exp B, Medium  -4.319   2.0000  8.319          (-----*-----)
                                        -+---------+---------+---------+-----
                                       -10         0        10        20
```

Condition ExF = Exp B, Low subtracted from:

```
Condition ExF   Lower  Center  Upper   -+---------+---------+---------+-----
Exp B, Medium  -3.764   2.556  8.875          (------*-----)
                                       -+---------+---------+---------+-----
                                      -10         0        10        20
```

Tukey Simultaneous Tests
Response Variable Error ExF
All Pairwise Comparisons among Levels of Condition ExF
Condition ExF = Exp A, High subtracted from:

Condition ExF	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Low	11.222	2.218	5.061	0.0000
Exp A, Medium	6.278	2.218	2.831	0.0527
Exp B, High	12.333	2.218	5.562	0.0000
Exp B, Low	11.778	2.218	5.311	0.0000
Exp B, Medium	14.333	2.218	6.464	0.0000

Condition ExF = Exp A, Low subtracted from:

Condition ExF	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Medium	-4.944	2.218	-2.230	0.2240
Exp B, High	1.111	2.218	0.501	0.9961
Exp B, Low	0.556	2.218	0.251	0.9999
Exp B, Medium	3.111	2.218	1.403	0.7253

Condition ExF = Exp A, Medium subtracted from:

Condition ExF	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, High	6.056	2.218	2.731	0.0693
Exp B, Low	5.500	2.218	2.480	0.1299
Exp B, Medium	8.056	2.218	3.633	0.0038

Condition ExF = Exp B, High subtracted from:

Condition ExF	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Low	-0.5556	2.218	-0.2505	0.9999
Exp B, Medium	2.0000	2.218	0.9019	0.9461

```
Condition ExF = Exp B, Low  subtracted from:

               Difference       SE of           Adjusted
Condition ExF    of Means  Difference  T-Value   P-Value
Exp B, Medium       2.556       2.218    1.152    0.8592
```

<u>Interaction Effects: Replication x Experiment x Force Level</u>

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error all
All Pairwise Comparisons among Levels of Condition all
Condition all = Exp A, Rep 1, High  subtracted from:

Condition all          Lower  Center   Upper
Exp A, Rep 1, Low      -0.68   9.333  19.344
Exp A, Rep 1, Medium   -0.34   9.667  19.678
Exp A, Rep 2, High    -16.57  -6.556   3.455
Exp A, Rep 2, Low      -3.46   6.556  16.567
Exp A, Rep 2, Medium  -13.68  -3.667   6.344
Exp B, Rep 1, High     -3.90   6.111  16.122
Exp B, Rep 1, Low      -0.34   9.667  19.678
Exp B, Rep 1, Medium    3.54  13.556  23.567
Exp B, Rep 2, High      1.99  12.000  22.011
Exp B, Rep 2, Low      -2.68   7.333  17.344
Exp B, Rep 2, Medium   -1.46   8.556  18.567

Condition all         ------+---------+---------+---------+
Exp A, Rep 1, Low                     (-----*-----)
Exp A, Rep 1, Medium                  (-----*-----)
Exp A, Rep 2, High          (-----*-----)
Exp A, Rep 2, Low                   (-----*-----)
Exp A, Rep 2, Medium         (------*-----)
Exp B, Rep 1, High                  (-----*-----)
Exp B, Rep 1, Low                     (-----*-----)
Exp B, Rep 1, Medium                    (-----*------)
Exp B, Rep 2, High                     (-----*------)
Exp B, Rep 2, Low                   (------*-----)
Exp B, Rep 2, Medium                 (-----*------)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp A, Rep 1, Low  subtracted from:

Condition all          Lower  Center   Upper
Exp A, Rep 1, Medium   -9.68    0.33  10.344
Exp A, Rep 2, High    -25.90  -15.89  -5.878
Exp A, Rep 2, Low     -12.79   -2.78   7.233
Exp A, Rep 2, Medium  -23.01  -13.00  -2.989
Exp B, Rep 1, High    -13.23   -3.22   6.789
Exp B, Rep 1, Low      -9.68    0.33  10.344
Exp B, Rep 1, Medium   -5.79    4.22  14.233
Exp B, Rep 2, High     -7.34    2.67  12.678
Exp B, Rep 2, Low     -12.01   -2.00   8.011
Exp B, Rep 2, Medium  -10.79   -0.78   9.233

Condition all         ------+---------+---------+---------+
Exp A, Rep 1, Medium            (-----*-----)
Exp A, Rep 2, High    (-----*-----)
Exp A, Rep 2, Low             (-----*------)
```

```
Exp A, Rep 2, Medium    (-----*-----)
Exp B, Rep 1, High            (-----*-----)
Exp B, Rep 1, Low               (-----*-----)
Exp B, Rep 1, Medium              (------*-----)
Exp B, Rep 2, High               (------*-----)
Exp B, Rep 2, Low             (------*-----)
Exp B, Rep 2, Medium           (------*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp A, Rep 1, Medium  subtracted from:

Condition all          Lower  Center   Upper
Exp A, Rep 2, High    -26.23  -16.22  -6.211
Exp A, Rep 2, Low     -13.12   -3.11   6.900
Exp A, Rep 2, Medium  -23.34  -13.33  -3.322
Exp B, Rep 1, High    -13.57   -3.56   6.455
Exp B, Rep 1, Low     -10.01    0.00  10.011
Exp B, Rep 1, Medium   -6.12    3.89  13.900
Exp B, Rep 2, High     -7.68    2.33  12.344
Exp B, Rep 2, Low     -12.34   -2.33   7.678
Exp B, Rep 2, Medium  -11.12   -1.11   8.900

Condition all         ------+---------+---------+---------+
Exp A, Rep 2, High    (-----*-----)
Exp A, Rep 2, Low             (-----*-----)
Exp A, Rep 2, Medium   (------*-----)
Exp B, Rep 1, High            (-----*-----)
Exp B, Rep 1, Low               (-----*-----)
Exp B, Rep 1, Medium              (-----*------)
Exp B, Rep 2, High               (-----*------)
Exp B, Rep 2, Low             (------*-----)
Exp B, Rep 2, Medium           (-----*------)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp A, Rep 2, High  subtracted from:

Condition all          Lower  Center  Upper
Exp A, Rep 2, Low      3.100  13.111  23.12
Exp A, Rep 2, Medium  -7.122   2.889  12.90
Exp B, Rep 1, High     2.656  12.667  22.68
Exp B, Rep 1, Low      6.211  16.222  26.23
Exp B, Rep 1, Medium  10.100  20.111  30.12
Exp B, Rep 2, High     8.545  18.556  28.57
Exp B, Rep 2, Low      3.878  13.889  23.90
Exp B, Rep 2, Medium   5.100  15.111  25.12

Condition all         ------+---------+---------+---------+
Exp A, Rep 2, Low                       (-----*-----)
Exp A, Rep 2, Medium              (-----*-----)
Exp B, Rep 1, High                      (-----*-----)
Exp B, Rep 1, Low                         (-----*-----)
Exp B, Rep 1, Medium                        (------*-----)
Exp B, Rep 2, High                         (------*-----)
Exp B, Rep 2, Low                       (------*-----)
Exp B, Rep 2, Medium                     (-----*------)
                      ------+---------+---------+---------+
                          -16         0        16        32
```

```
Condition all = Exp A, Rep 2, Low  subtracted from:

Condition all          Lower  Center    Upper
Exp A, Rep 2, Medium  -20.23  -10.22  -0.2112
Exp B, Rep 1, High    -10.46   -0.44   9.5666
Exp B, Rep 1, Low      -6.90    3.11  13.1221
Exp B, Rep 1, Medium   -3.01    7.00  17.0110
Exp B, Rep 2, High     -4.57    5.44  15.4554
Exp B, Rep 2, Low      -9.23    0.78  10.7888
Exp B, Rep 2, Medium   -8.01    2.00  12.0110

Condition all         ------+---------+---------+---------+
Exp A, Rep 2, Medium     (------*-----)
Exp B, Rep 1, High             (------*-----)
Exp B, Rep 1, Low                 (-----*-----)
Exp B, Rep 1, Medium                (-----*------)
Exp B, Rep 2, High                 (-----*------)
Exp B, Rep 2, Low               (-----*------)
Exp B, Rep 2, Medium             (-----*------)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp A, Rep 2, Medium  subtracted from:

Condition all           Lower  Center  Upper
Exp B, Rep 1, High    -0.2332   9.778  19.79
Exp B, Rep 1, Low      3.3223  13.333  23.34
Exp B, Rep 1, Medium   7.2112  17.222  27.23
Exp B, Rep 2, High     5.6557  15.667  25.68
Exp B, Rep 2, Low      0.9890  11.000  21.01
Exp B, Rep 2, Medium   2.2112  12.222  22.23

Condition all         ------+---------+---------+---------+
Exp B, Rep 1, High                    (-----*-----)
Exp B, Rep 1, Low                       (-----*------)
Exp B, Rep 1, Medium                       (-----*-----)
Exp B, Rep 2, High                        (-----*-----)
Exp B, Rep 2, Low                      (-----*-----)
Exp B, Rep 2, Medium                   (------*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp B, Rep 1, High  subtracted from:

Condition all          Lower  Center  Upper
Exp B, Rep 1, Low     -6.455   3.556  13.57
Exp B, Rep 1, Medium  -2.567   7.444  17.46
Exp B, Rep 2, High    -4.122   5.889  15.90
Exp B, Rep 2, Low     -8.789   1.222  11.23
Exp B, Rep 2, Medium  -7.567   2.444  12.46

Condition all         ------+---------+---------+---------+
Exp B, Rep 1, Low                 (-----*-----)
Exp B, Rep 1, Medium                (------*-----)
Exp B, Rep 2, High                 (------*-----)
Exp B, Rep 2, Low               (-----*-----)
Exp B, Rep 2, Medium            (------*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32
```

```
Condition all = Exp B, Rep 1, Low  subtracted from:

Condition all          Lower  Center   Upper
Exp B, Rep 1, Medium   -6.12   3.889  13.900
Exp B, Rep 2, High     -7.68   2.333  12.344
Exp B, Rep 2, Low     -12.34  -2.333   7.678
Exp B, Rep 2, Medium  -11.12  -1.111   8.900

Condition all         ------+---------+---------+---------+
Exp B, Rep 1, Medium             (-----*------)
Exp B, Rep 2, High              (-----*------)
Exp B, Rep 2, Low            (------*-----)
Exp B, Rep 2, Medium          (-----*------)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp B, Rep 1, Medium  subtracted from:

Condition all          Lower  Center  Upper
Exp B, Rep 2, High    -11.57  -1.556  8.455
Exp B, Rep 2, Low     -16.23  -6.222  3.789
Exp B, Rep 2, Medium  -15.01  -5.000  5.011

Condition all         ------+---------+---------+---------+
Exp B, Rep 2, High            (-----*-----)
Exp B, Rep 2, Low          (-----*-----)
Exp B, Rep 2, Medium        (-----*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp B, Rep 2, High  subtracted from:

Condition all          Lower  Center  Upper
Exp B, Rep 2, Low     -14.68  -4.667  5.344
Exp B, Rep 2, Medium  -13.46  -3.444  6.567

Condition all         ------+---------+---------+---------+
Exp B, Rep 2, Low           (-----*-----)
Exp B, Rep 2, Medium         (-----*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32


Condition all = Exp B, Rep 2, Low  subtracted from:

Condition all          Lower  Center  Upper
Exp B, Rep 2, Medium  -8.789   1.222  11.23

Condition all         ------+---------+---------+---------+
Exp B, Rep 2, Medium            (-----*-----)
                      ------+---------+---------+---------+
                          -16         0        16        32


Tukey Simultaneous Tests
Response Variable Error all
All Pairwise Comparisons among Levels of Condition all
Condition all = Exp A, Rep 1, High  subtracted from:

                      Difference       SE of           Adjusted
Condition all           of Means  Difference  T-Value   P-Value
```

Exp A, Rep 1, Low	9.333	3.064	3.046	0.0958
Exp A, Rep 1, Medium	9.667	3.064	3.154	0.0703
Exp A, Rep 2, High	-6.556	3.064	-2.139	0.5942
Exp A, Rep 2, Low	6.556	3.064	2.139	0.5942
Exp A, Rep 2, Medium	-3.667	3.064	-1.197	0.9893
Exp B, Rep 1, High	6.111	3.064	1.994	0.6977
Exp B, Rep 1, Low	9.667	3.064	3.154	0.0703
Exp B, Rep 1, Medium	13.556	3.064	4.424	0.0006
Exp B, Rep 2, High	12.000	3.064	3.916	0.0051
Exp B, Rep 2, Low	7.333	3.064	2.393	0.4106
Exp B, Rep 2, Medium	8.556	3.064	2.792	0.1833

Condition all = Exp A, Rep 1, Low subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Rep 1, Medium	0.33	3.064	0.109	1.0000
Exp A, Rep 2, High	-15.89	3.064	-5.185	0.0000
Exp A, Rep 2, Low	-2.78	3.064	-0.906	0.9991
Exp A, Rep 2, Medium	-13.00	3.064	-4.242	0.0014
Exp B, Rep 1, High	-3.22	3.064	-1.051	0.9965
Exp B, Rep 1, Low	0.33	3.064	0.109	1.0000
Exp B, Rep 1, Medium	4.22	3.064	1.378	0.9679
Exp B, Rep 2, High	2.67	3.064	0.870	0.9994
Exp B, Rep 2, Low	-2.00	3.064	-0.653	1.0000
Exp B, Rep 2, Medium	-0.78	3.064	-0.254	1.0000

Condition all = Exp A, Rep 1, Medium subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Rep 2, High	-16.22	3.064	-5.294	0.0000
Exp A, Rep 2, Low	-3.11	3.064	-1.015	0.9974
Exp A, Rep 2, Medium	-13.33	3.064	-4.351	0.0008
Exp B, Rep 1, High	-3.56	3.064	-1.160	0.9917
Exp B, Rep 1, Low	0.00	3.064	0.000	1.0000
Exp B, Rep 1, Medium	3.89	3.064	1.269	0.9829
Exp B, Rep 2, High	2.33	3.064	0.761	0.9998
Exp B, Rep 2, Low	-2.33	3.064	-0.761	0.9998
Exp B, Rep 2, Medium	-1.11	3.064	-0.363	1.0000

Condition all = Exp A, Rep 2, High subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Rep 2, Low	13.111	3.064	4.2785	0.0012
Exp A, Rep 2, Medium	2.889	3.064	0.9427	0.9987
Exp B, Rep 1, High	12.667	3.064	4.1334	0.0021
Exp B, Rep 1, Low	16.222	3.064	5.2937	0.0000
Exp B, Rep 1, Medium	20.111	3.064	6.5627	0.0000
Exp B, Rep 2, High	18.556	3.064	6.0551	0.0000
Exp B, Rep 2, Low	13.889	3.064	4.5323	0.0004
Exp B, Rep 2, Medium	15.111	3.064	4.9311	0.0001

Condition all = Exp A, Rep 2, Low subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp A, Rep 2, Medium	-10.22	3.064	-3.336	0.0405

Exp B, Rep 1, High	-0.44	3.064	-0.145	1.0000
Exp B, Rep 1, Low	3.11	3.064	1.015	0.9974
Exp B, Rep 1, Medium	7.00	3.064	2.284	0.4879
Exp B, Rep 2, High	5.44	3.064	1.777	0.8310
Exp B, Rep 2, Low	0.78	3.064	0.254	1.0000
Exp B, Rep 2, Medium	2.00	3.064	0.653	1.0000

Condition all = Exp A, Rep 2, Medium subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 1, High	9.778	3.064	3.191	0.0632
Exp B, Rep 1, Low	13.333	3.064	4.351	0.0008
Exp B, Rep 1, Medium	17.222	3.064	5.620	0.0000
Exp B, Rep 2, High	15.667	3.064	5.112	0.0000
Exp B, Rep 2, Low	11.000	3.064	3.590	0.0173
Exp B, Rep 2, Medium	12.222	3.064	3.988	0.0039

Condition all = Exp B, Rep 1, High subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 1, Low	3.556	3.064	1.1603	0.9917
Exp B, Rep 1, Medium	7.444	3.064	2.4293	0.3859
Exp B, Rep 2, High	5.889	3.064	1.9217	0.7458
Exp B, Rep 2, Low	1.222	3.064	0.3988	1.0000
Exp B, Rep 2, Medium	2.444	3.064	0.7977	0.9997

Condition all = Exp B, Rep 1, Low subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 1, Medium	3.889	3.064	1.2690	0.9829
Exp B, Rep 2, High	2.333	3.064	0.7614	0.9998
Exp B, Rep 2, Low	-2.333	3.064	-0.7614	0.9998
Exp B, Rep 2, Medium	-1.111	3.064	-0.3626	1.0000

Condition all = Exp B, Rep 1, Medium subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 2, High	-1.556	3.064	-0.508	1.0000
Exp B, Rep 2, Low	-6.222	3.064	-2.030	0.6725
Exp B, Rep 2, Medium	-5.000	3.064	-1.632	0.8977

Condition all = Exp B, Rep 2, High subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 2, Low	-4.667	3.064	-1.523	0.9346
Exp B, Rep 2, Medium	-3.444	3.064	-1.124	0.9937

Condition all = Exp B, Rep 2, Low subtracted from:

Condition all	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
Exp B, Rep 2, Medium	1.222	3.064	0.3988	1.000

Appendix D: Analysis of Variance for Fatigued Strength Estimation Error

Estimation Error ANOVA

General Linear Model: Error versus Subject, Order, Fatiguing task force

Factor	Type	Levels	Values
Subject	random	15	1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15
Order	fixed	3	1, 2, 3
Fatiguing task force	fixed	3	0.25, 0.50, 0.75

Analysis of Variance for Error, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	14	3373.87	2154.64	153.90	2.10	0.057
Order	2	673.73	124.83	62.42	0.85	0.440
Fatiguing task force	2	961.14	1092.25	546.13	7.47	0.003
Order*Fatiguing task force	4	725.24	725.24	181.31	2.48	0.074
Error	22	1609.23	1609.23	73.15		
Total	44	7343.20				

S = 8.55258   R-Sq = 78.09%   R-Sq(adj) = 56.17%

Main Effects: Order

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Order
Order = 1 subtracted from:

```
Order   Lower  Center  Upper   ---+---------+---------+---------+---
2      -12.67  -2.631  7.404     (----------------*---------------)
3      -14.00  -4.787  4.422   (--------------*--------------)
                               ---+---------+---------+---------+---
                              -12.0      -6.0       0.0       6.0
```

Order = 2 subtracted from:

```
Order   Lower  Center  Upper   ---+---------+---------+---------+---
3      -11.37  -2.156  7.054       (--------------*---------------)
                               ---+---------+---------+---------+---
                              -12.0      -6.0       0.0       6.0
```

Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Order
Order = 1 subtracted from:

Order	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
2	-2.631	3.998	-0.658	0.7897
3	-4.787	3.669	-1.305	0.4075

```
Order = 2  subtracted from:

       Difference       SE of           Adjusted
Order    of Means  Difference  T-Value   P-Value
3          -2.156       3.669  -0.5876    0.8281
```

Main Effects: Fatiguing Task Force

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Fatiguing task force
Fatiguing task force = 0.25  subtracted from:

Fatiguing
task force   Lower  Center   Upper  ---+---------+---------+---------+---
0.50        -22.58  -13.37  -4.161  (---------*--------)
0.75        -18.95   -9.74  -0.530      (--------*--------)
                                    ---+---------+---------+---------+---
                                     -20       -10         0        10


Fatiguing task force = 0.50  subtracted from:

Fatiguing
task force   Lower  Center  Upper  ---+---------+---------+---------+---
0.75        -6.404   3.631  13.67                   (---------*---------)
                                   ---+---------+---------+---------+---
                                    -20       -10         0        10


Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Fatiguing task force
Fatiguing task force = 0.25  subtracted from:

Fatiguing   Difference       SE of           Adjusted
task force    of Means  Difference  T-Value   P-Value
0.50            -13.37       3.669   -3.644    0.0039
0.75             -9.74       3.669   -2.655    0.0371


Fatiguing task force = 0.50  subtracted from:

Fatiguing   Difference       SE of           Adjusted
task force    of Means  Difference  T-Value   P-Value
0.75             3.631       3.998   0.9083    0.6409
```

Interaction Effects: Order x Fatiguing Task Force

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Error
All Pairwise Comparisons among Levels of Condition
Condition = 25%, 1st  subtracted from:

Condition   Lower  Center   Upper  ------+---------+---------+---------+
25%, 2nd   -21.78   -1.34  19.092          (------*-----)
25%, 3rd   -33.74  -11.10  11.536      (------*-------)
50%, 1st   -48.96  -20.72   7.514  (--------*---------)
50%, 2nd   -38.48  -18.72   1.041    (------*-----)
50%, 3rd   -25.52   -5.08  15.351        (------*------)
75%, 1st   -22.28   -3.04  16.200          (-----*-----)
```

```
75%, 2nd   -46.80  -18.56   9.675  (---------*--------)
75%, 3rd   -46.48  -25.13  -3.788   (------*------)
                                   ------+---------+---------+---------+
                                       -30         0        30        60


Condition = 25%, 2nd  subtracted from:

Condition   Lower  Center   Upper  ------+---------+---------+---------+
25%, 3rd   -31.54   -9.76  12.024       (-------*------)
50%, 1st   -46.93  -19.38   8.177  (---------*--------)
50%, 2nd   -36.15  -17.38   1.399      (-----*-----)
50%, 3rd   -23.23   -3.74  15.743          (------*-----)
75%, 1st   -19.92   -1.70  16.530           (-----*------)
75%, 2nd   -44.77  -17.22  10.338   (--------*--------)
75%, 3rd   -44.22  -23.79  -3.354   (------*------)
                                   ------+---------+---------+---------+
                                       -30         0        30        60


Condition = 25%, 3rd  subtracted from:

Condition   Lower  Center   Upper  ------+---------+---------+---------+
50%, 1st   -38.84   -9.62  19.608     (---------*---------)
50%, 2nd   -28.77   -7.62  13.536        (------*-------)
50%, 3rd   -15.77    6.02  27.803             (------*------)
75%, 1st   -12.60    8.06  28.730              (------*------)
75%, 2nd   -36.68   -7.46  21.769      (---------*--------)
75%, 3rd   -36.67  -14.03   8.609      (------*-------)
                                   ------+---------+---------+---------+
                                       -30         0        30        60


Condition = 50%, 1st  subtracted from:

Condition   Lower  Center  Upper  ------+---------+---------+---------+
50%, 2nd   -25.06   2.002  29.06          (--------*--------)
50%, 3rd   -11.92  15.637  43.19              (--------*--------)
75%, 1st    -9.00  17.682  44.36               (--------*--------)
75%, 2nd   -31.59   2.161  35.91       (-----------*----------)
75%, 3rd   -32.65  -4.411  23.82       (---------*--------)
                                  ------+---------+---------+---------+
                                      -30         0        30        60


Condition = 50%, 2nd  subtracted from:

Condition   Lower  Center  Upper  ------+---------+---------+---------+
50%, 3rd    -5.14  13.635  32.41                (------*-----)
75%, 1st    -1.79  15.680  33.15                 (-----*-----)
75%, 2nd   -26.90   0.159  27.22         (--------*--------)
75%, 3rd   -26.17  -6.413  13.35         (------*-----)
                                  ------+---------+---------+---------+
                                      -30         0        30        60


Condition = 50%, 3rd  subtracted from:

Condition   Lower  Center    Upper  ------+---------+---------+---------+
75%, 1st   -16.18    2.04  20.2707              (-----*-----)
75%, 2nd   -41.03  -13.48  14.0789    (---------*--------)
75%, 3rd   -40.48  -20.05   0.3870     (-----*------)
                                    ------+---------+---------+---------+
```

```
                                        -30         0        30        60
```

Condition = 75%, 1st subtracted from:

```
Condition   Lower  Center   Upper  ------+---------+---------+---------+
75%, 2nd   -42.20  -15.52  11.159    (--------*--------)
75%, 3rd   -41.33  -22.09  -2.854    (------*-----)
                                   ------+---------+---------+---------+
                                       -30         0        30        60
```

Condition = 75%, 2nd subtracted from:

```
Condition   Lower  Center  Upper  ------+---------+---------+---------+
75%, 3rd   -34.81  -6.572  21.66      (---------*--------)
                                  ------+---------+---------+---------+
                                      -30         0        30        60
```

Tukey Simultaneous Tests
Response Variable Error
All Pairwise Comparisons among Levels of Condition
Condition = 25%, 1st subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
25%, 2nd	-1.34	6.202	-0.217	1.0000
25%, 3rd	-11.10	6.870	-1.616	0.7899
50%, 1st	-20.72	8.569	-2.418	0.3053
50%, 2nd	-18.72	5.997	-3.121	0.0754
50%, 3rd	-5.08	6.202	-0.820	0.9955
75%, 1st	-3.04	5.839	-0.521	0.9998
75%, 2nd	-18.56	8.569	-2.166	0.4478
75%, 3rd	-25.13	6.477	-3.880	0.0113

Condition = 25%, 2nd subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
25%, 3rd	-9.76	6.611	-1.476	0.8589
50%, 1st	-19.38	8.362	-2.317	0.3589
50%, 2nd	-17.38	5.698	-3.050	0.0886
50%, 3rd	-3.74	5.913	-0.633	0.9993
75%, 1st	-1.70	5.531	-0.307	1.0000
75%, 2nd	-17.22	8.362	-2.059	0.5153
75%, 3rd	-23.79	6.202	-3.836	0.0127

Condition = 25%, 3rd subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 1st	-9.62	8.870	-1.084	0.9729
50%, 2nd	-7.62	6.419	-1.186	0.9543
50%, 3rd	6.02	6.611	0.910	0.9909
75%, 1st	8.06	6.272	1.286	0.9291
75%, 2nd	-7.46	8.870	-0.841	0.9946
75%, 3rd	-14.03	6.870	-2.042	0.5261

Condition = 50%, 1st subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 2nd	2.002	8.212	0.2438	1.0000
50%, 3rd	15.637	8.362	1.8700	0.6374
75%, 1st	17.682	8.097	2.1838	0.4369
75%, 2nd	2.161	10.242	0.2110	1.0000
75%, 3rd	-4.411	8.569	-0.5148	0.9998

Condition = 50%, 2nd subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 3rd	13.635	5.698	2.393	0.3182
75%, 1st	15.680	5.301	2.958	0.1082
75%, 2nd	0.159	8.212	0.019	1.0000
75%, 3rd	-6.413	5.997	-1.069	0.9751

Condition = 50%, 3rd subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 1st	2.04	5.531	0.370	1.0000
75%, 2nd	-13.48	8.362	-1.612	0.7924
75%, 3rd	-20.05	6.202	-3.233	0.0583

Condition = 75%, 1st subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 2nd	-15.52	8.097	-1.917	0.6071
75%, 3rd	-22.09	5.839	-3.784	0.0146

Condition = 75%, 2nd subtracted from:

Condition	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 3rd	-6.572	8.569	-0.7670	0.9971

Appendix E: Analysis of Variance for Perceived Discomfort of Fatiguing Task

Perceived Discomfort ANOVA

General Linear Model: Perceived di versus Subject, Order, Fatiguing ta

```
Factor                Type    Levels  Values
Subject               random      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,
                                      13, 14, 15
Order                 fixed        3  1, 2, 3
Fatiguing task force  fixed        3  0.25, 0.50, 0.75


Analysis of Variance for Perceived discomfort, using Adjusted SS for Tests

Source                      DF   Seq SS  Adj SS  Adj MS      F      P
Subject                     14  101.495  80.629   5.759   7.51  0.000
Order                        2   15.024   4.495   2.248   2.93  0.074
Fatiguing task force         2  116.258  95.267  47.634  62.14  0.000
Order*Fatiguing task force   4    4.947   4.947   1.237   1.61  0.206
Error                       22   16.864  16.864   0.767
Total                       44  254.588


S = 0.875539   R-Sq = 93.38%   R-Sq(adj) = 86.75%
```

Main Effects: Order

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Perceived discomfort
All Pairwise Comparisons among Levels of Order
Order = 1  subtracted from:

Order   Lower   Center   Upper  ------+---------+---------+---------+
2      -1.605  -0.5772  0.4502  (---------*----------)
3      -0.611   0.3313  1.2741            (--------*---------)
                                ------+---------+---------+---------+
                                   -1.0       0.0       1.0       2.0


Order = 2  subtracted from:

Order     Lower  Center  Upper  ------+---------+---------+---------+
3      -0.03422  0.9086  1.851                  (--------*---------)
                                ------+---------+---------+---------+
                                   -1.0       0.0       1.0       2.0


Tukey Simultaneous Tests
Response Variable Perceived discomfort
All Pairwise Comparisons among Levels of Order
Order = 1  subtracted from:

       Difference       SE of           Adjusted
Order    of Means  Difference  T-Value   P-Value
2         -0.5772      0.4093   -1.410    0.3530
3          0.3313      0.3756    0.882    0.6569
```

```
Order = 2  subtracted from:

       Difference       SE of            Adjusted
Order    of Means  Difference  T-Value   P-Value
3          0.9086      0.3756    2.419    0.0605
```

Main Effects: Fatiguing Task Force

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Perceived discomfort
All Pairwise Comparisons among Levels of Fatiguing task force
Fatiguing task force = 0.25  subtracted from:

Fatiguing
task force  Lower  Center  Upper    +---------+---------+---------+------
0.50        1.930   2.873  3.816                 (-----*-----)
0.75        3.007   3.950  4.893                        (-----*------)
                                    +---------+---------+---------+------
                                  0.0       1.5       3.0       4.5


Fatiguing task force = 0.50  subtracted from:

Fatiguing
task force    Lower  Center  Upper    +---------+---------+---------+------
0.75        0.04984   1.077  2.105    (------*------)
                                      +---------+---------+---------+------
                                    0.0       1.5       3.0       4.5


Tukey Simultaneous Tests
Response Variable Perceived discomfort
All Pairwise Comparisons among Levels of Fatiguing task force
Fatiguing task force = 0.25  subtracted from:

Fatiguing   Difference       SE of            Adjusted
task force    of Means  Difference  T-Value   P-Value
0.50             2.873      0.3756    7.650    0.0000
0.75             3.950      0.3756   10.518    0.0000


Fatiguing task force = 0.50  subtracted from:

Fatiguing   Difference       SE of            Adjusted
task force    of Means  Difference  T-Value   P-Value
0.75             1.077      0.4093    2.632    0.0389
```

Interaction Effects: Order x Fatiguing Task Force

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Value
All Pairwise Comparisons among Levels of Condition PD
Condition PD = 25%, 1st  subtracted from:

Condition PD   Lower   Center  Upper  ----+---------+---------+---------+--
25%, 2nd      -3.524  -0.2400  3.044         (------*-----)
25%, 3rd      -3.253   0.3850  4.023         (-------*------)
50%, 1st       0.223   4.7600  9.297                (---------*--------)
50%, 2nd      -0.629   2.5457  5.721               (-----*-----)
50%, 3rd      -1.024   2.2600  5.544              (------*-----)
75%, 1st       0.169   3.2600  6.351                (------*-----)
```

```
75%, 2nd      -1.527   3.0100  7.547             (--------*--------)
75%, 3rd       2.230   5.6600  9.090                    (------*------)
                                      ----+---------+---------+---------+--
                                       -5.0       0.0       5.0      10.0


Condition PD = 25%, 2nd  subtracted from:

Condition PD   Lower  Center  Upper  ----+---------+---------+---------+--
25%, 3rd      -2.875  0.6250  4.125          (------*------)
50%, 1st       0.572  5.0000  9.428                 (--------*--------)
50%, 2nd      -0.231  2.7857  5.803                (-----*-----)
50%, 3rd      -0.631  2.5000  5.631               (-----*-----)
75%, 1st       0.571  3.5000  6.429                 (-----*-----)
75%, 2nd      -1.178  3.2500  7.678              (--------*-------)
75%, 3rd       2.616  5.9000  9.184                     (------*-----)
                                     ----+---------+---------+---------+--
                                      -5.0       0.0       5.0      10.0


Condition PD = 25%, 3rd  subtracted from:

Condition PD   Lower  Center  Upper  ----+---------+---------+---------+--
50%, 1st      -0.321   4.375  9.071               (---------*--------)
50%, 2nd      -1.238   2.161  5.560              (-----*------)
50%, 3rd      -1.625   1.875  5.375             (------*------)
75%, 1st      -0.446   2.875  6.196               (------*-----)
75%, 2nd      -2.071   2.625  7.321            (--------*---------)
75%, 3rd       1.637   5.275  8.913                   (-------*------)
                                     ----+---------+---------+---------+--
                                      -5.0       0.0       5.0      10.0


Condition PD = 50%, 1st  subtracted from:

Condition PD   Lower  Center  Upper  ----+---------+---------+---------+--
50%, 2nd      -6.562  -2.214  2.133   (--------*-------)
50%, 3rd      -6.928  -2.500  1.928  (--------*--------)
75%, 1st      -5.787  -1.500  2.787    (--------*--------)
75%, 2nd      -7.173  -1.750  3.673  (----------*---------)
75%, 3rd      -3.637   0.900  5.437         (--------*--------)
                                     ----+---------+---------+---------+--
                                      -5.0       0.0       5.0      10.0


Condition PD = 50%, 2nd  subtracted from:

Condition PD   Lower   Center  Upper  ----+---------+---------+---------+--
50%, 3rd      -3.303  -0.2857  2.731         (-----*-----)
75%, 1st      -2.092   0.7143  3.521            (----*-----)
75%, 2nd      -3.883   0.4643  4.812        (--------*--------)
75%, 3rd      -0.061   3.1143  6.289                (-----*------)
                                      ----+---------+---------+---------+--
                                       -5.0       0.0       5.0      10.0


Condition PD = 50%, 3rd  subtracted from:

Condition PD   Lower  Center  Upper  ----+---------+---------+---------+--
75%, 1st      -1.929  1.0000  3.929            (-----*-----)
75%, 2nd      -3.678  0.7500  5.178         (-------*--------)
75%, 3rd       0.116  3.4000  6.684                (------*-----)
                                     ----+---------+---------+---------+--
```

```
                                        -5.0       0.0       5.0      10.0
```

Condition PD = 75%, 1st subtracted from:

```
Condition PD   Lower   Center  Upper  ----+---------+---------+---------+--
75%, 2nd      -4.537  -0.2500  4.037       (--------*-------)
75%, 3rd      -0.691   2.4000  5.491               (-----*-----)
                                      ----+---------+---------+---------+--
                                       -5.0       0.0       5.0      10.0
```

Condition PD = 75%, 2nd subtracted from:

```
Condition PD   Lower  Center  Upper  ----+---------+---------+---------+--
75%, 3rd      -1.887   2.650  7.187             (--------*--------)
                                     ----+---------+---------+---------+--
                                        -5.0       0.0       5.0      10.0
```

Tukey Simultaneous Tests
Response Variable Value
All Pairwise Comparisons among Levels of Condition PD
Condition PD = 25%, 1st subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
25%, 2nd	-0.2400	0.9965	-0.2408	1.0000
25%, 3rd	0.3850	1.1039	0.3488	1.0000
50%, 1st	4.7600	1.3768	3.4572	0.0339
50%, 2nd	2.5457	0.9636	2.6419	0.2053
50%, 3rd	2.2600	0.9965	2.2680	0.3869
75%, 1st	3.2600	0.9382	3.4749	0.0324
75%, 2nd	3.0100	1.3768	2.1862	0.4355
75%, 3rd	5.6600	1.0408	5.4381	0.0001

Condition PD = 25%, 2nd subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
25%, 3rd	0.6250	1.0623	0.5884	0.9996
50%, 1st	5.0000	1.3437	3.7212	0.0173
50%, 2nd	2.7857	0.9156	3.0427	0.0900
50%, 3rd	2.5000	0.9501	2.6313	0.2095
75%, 1st	3.5000	0.8887	3.9381	0.0097
75%, 2nd	3.2500	1.3437	2.4188	0.3050
75%, 3rd	5.9000	0.9965	5.9208	0.0001

Condition PD = 25%, 3rd subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 1st	4.375	1.425	3.070	0.0847
50%, 2nd	2.161	1.031	2.095	0.4923
50%, 3rd	1.875	1.062	1.765	0.7034
75%, 1st	2.875	1.008	2.853	0.1352
75%, 2nd	2.625	1.425	1.842	0.6554
75%, 3rd	5.275	1.104	4.778	0.0009

Condition PD = 50%, 1st subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 2nd	-2.214	1.319	-1.678	0.7552
50%, 3rd	-2.500	1.344	-1.861	0.6434
75%, 1st	-1.500	1.301	-1.153	0.9612
75%, 2nd	-1.750	1.646	-1.063	0.9759
75%, 3rd	0.900	1.377	0.654	0.9991

Condition PD = 50%, 2nd subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
50%, 3rd	-0.2857	0.9156	-0.3121	1.0000
75%, 1st	0.7143	0.8517	0.8387	0.9947
75%, 2nd	0.4643	1.3194	0.3519	1.0000
75%, 3rd	3.1143	0.9636	3.2320	0.0584

Condition PD = 50%, 3rd subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 1st	1.0000	0.8887	1.1252	0.9663
75%, 2nd	0.7500	1.3437	0.5582	0.9997
75%, 3rd	3.4000	0.9965	3.4120	0.0379

Condition PD = 75%, 1st subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 2nd	-0.2500	1.3010	-0.1922	1.0000
75%, 3rd	2.4000	0.9382	2.5582	0.2396

Condition PD = 75%, 2nd subtracted from:

Condition PD	Difference of Means	SE of Difference	T-Value	Adjusted P-Value
75%, 3rd	2.650	1.377	1.925	0.6021

Appendix F: Analysis of Variance of Strength Loss from Fatiguing Task

Strength Loss ANOVA

General Linear Model: Strength Loss versus Order, Fatiguing Ta, Subject

```
Factor                Type    Levels  Values
Order                 fixed        3  1, 2, 3
Fatiguing Task Force  fixed        3  25, 50, 75
Subject               random      15  1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12,
                                      13, 14, 15

Analysis of Variance for Strength Loss_1, using Adjusted SS for Tests

Source                      DF    Seq SS    Adj SS    Adj MS     F      P
Order                        2  0.040919  0.039299  0.019649  3.27  0.057
Fatiguing Task Force         2  0.085991  0.051979  0.025989  4.32  0.026
Subject                     14  0.213210  0.228422  0.016316  2.71  0.018
Order*Fatiguing Task Force   4  0.033736  0.033736  0.008434  1.40  0.266
Error                       22  0.132369  0.132369  0.006017
Total                       44  0.506225

S = 0.0775679   R-Sq = 73.85%   R-Sq(adj) = 47.70%
```

Main Effect: Fatiguing Task Force Level

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Strength Loss_1
All Pairwise Comparisons among Levels of Fatiguing Task Force
Fatiguing Task Force = 25  subtracted from:

Fatiguing
Task Force     Lower   Center   Upper  ---------+---------+---------+-------
50          -0.06601  0.01752  0.1010  (-----------*----------)
75           0.01151  0.09504  0.1786            (-----------*-----------)
                                       ---------+---------+---------+-------
                                            0.000     0.070     0.140

Fatiguing Task Force = 50  subtracted from:

Fatiguing
Task Force     Lower   Center   Upper  ---------+---------+---------+-------
75          -0.01350  0.07752  0.1685         (------------*-----------)
                                       ---------+---------+---------+-------
                                            0.000     0.070     0.140

Tukey Simultaneous Tests
Response Variable Strength Loss_1
All Pairwise Comparisons among Levels of Fatiguing Task Force
Fatiguing Task Force = 25  subtracted from:

Fatiguing   Difference       SE of           Adjusted
Task Force    of Means  Difference  T-Value   P-Value
50             0.01752     0.03327   0.5264    0.8593
75             0.09504     0.03327   2.8562    0.0240

Fatiguing Task Force = 50  subtracted from:

Fatiguing   Difference       SE of           Adjusted
Task Force    of Means  Difference  T-Value   P-Value
75             0.07752     0.03626    2.138    0.1052
```

Appendix G: Regression Analysis

Regression Analysis: Perceived Discomfort on Error

Regression Analysis: Error versus Perceived discomfort

```
The regression equation is
Error = - 1.71 - 2.22 Perceived discomfort

Predictor               Coef  SE Coef      T      P
Constant              -1.710    4.124  -0.41  0.681
Perceived discomfort  -2.2210   0.7457  -2.98  0.005

S = 11.8982   R-Sq = 17.1%   R-Sq(adj) = 15.2%

Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  1255.8  1255.8  8.87  0.005
Residual Error  43  6087.4   141.6
Total           44  7343.2
```

Regression of Strength Loss on Fatigued Strength Estimation Error

Regression Analysis: Error versus Strength Loss

```
The regression equation is
Error = - 15.4 + 26.8 Strength Loss

Predictor         Coef  SE Coef      T      P
Constant       -15.395    2.578  -5.97  0.000
Strength Loss    26.75    17.87   1.50  0.142

S = 12.7163   R-Sq = 5.0%   R-Sq(adj) = 2.7%

Analysis of Variance

Source          DF      SS     MS     F      P
Regression       1   362.4  362.4  2.24  0.142
Residual Error  43  6953.3  161.7
Total           44  7315.6
```

Regression of Strength Loss on Perceived Discomfort

Regression Analysis: Perceived Discomfort versus Strength Loss

```
The regression equation is
Perceived Discomfort = 4.15 + 8.63 Strength Loss_1

Predictor          Coef  SE Coef     T      P
Constant         4.1493   0.4553  9.11  0.000
Strength Loss_1   8.633    3.156  2.74  0.009

S = 2.24570   R-Sq = 14.8%   R-Sq(adj) = 12.8%

Analysis of Variance

Source          DF       SS      MS     F      P
Regression       1   37.731  37.731  7.48  0.009
Residual Error  43  216.857   5.043
Total           44  254.588
```